### Actuators 1

**Chair Kyu-Jin Cho, Seoul National University, Biorobotics Laboratory**  
**Co-Chair Hideyuki Tsukagoshi, Tokyo Institute of Technology**

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<tr>
<th>Time</th>
<th>Session TUA1</th>
<th>Topic</th>
<th>Authors/Institutions</th>
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<tr>
<td>09:55–10:00</td>
<td>TUA1.1</td>
<td>A structure preserving nondimensionalization of hydraulic rotational joints</td>
<td>Satoru Sakai</td>
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<td></td>
<td></td>
<td>• The original model of hydraulic joints is complex.</td>
<td>Department of Mechanical Engineering, Shinshu University, Japan</td>
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<td></td>
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<td>• However, the model is exactly simplified by our special nondimensionalization.</td>
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<td>• In our opinion, the several advantages: Simulor Applicability, Faster Dynamics Computation, Efficient Parameter Update, ...</td>
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<td>• should be highlighted even for 1-DOF case in academic or industrial points of view.</td>
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<tr>
<td>10:05–10:10</td>
<td>TUA1.3</td>
<td>Toward Compliant, Fast, High-Precision, and Low-Cost Manipulator with Hydraulic Hybrid Servo Booster</td>
<td>Sang-Ho Hyon, Sumihito Tanimoto and Shota Asao</td>
</tr>
<tr>
<td></td>
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<td>• Novel hydraulic hybrid servo drive is first applied to a robotic manipulator</td>
<td>Department of Robotics, Ritsumeikan University, Japan</td>
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<td>• High-speed, large torque, high-precision control are possible at low cost</td>
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<td>• Compliant motion is achieved with the intrinsic backdrivability of the small servo-pump</td>
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<td>• Experimental results include a simple slider tested and a planar three-axis manipulator (video attached)</td>
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<td>10:15–10:20</td>
<td>TUA1.4</td>
<td>Design of a Structure-Controlled Variable Stiffness Actuator Based on Rotary Flexure Hinges</td>
<td>Xiong Li, Wenjie Chen and Wei Lin</td>
</tr>
<tr>
<td></td>
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<td>• The rotational stiffness is theoretically constant for the full range of the applied torque at any particular stiffness setting</td>
<td>Mechatronics Group, Singapore Institute of Manufacturing Technology (SIMTech), A*STAR, Singapore</td>
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<td></td>
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<td>• No additional torque is applied for holding a stiffness constant</td>
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<td>• Outputs of the actuator for the position and the stiffness are independently controlled</td>
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<td>• Low inertia and friction force</td>
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<td>10:20–10:25</td>
<td>TUA1.5</td>
<td>Intrinsically Backdrivable Hydraulic Servovalve for Interactive Robot control</td>
<td>Sunkyum Yoo, Woogyoung Lee and Wan Kyun Chung</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Backdrivability brings force transmission, low gear ratio and low output impedance to the mechanical systems</td>
<td>Mechanical Engineering, POSTECH, Republic of Korea</td>
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<td>• Conventional servovalve-based Hydraulic actuators lack the capability to interact with the environment due to its non-backdrivable structure.</td>
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<td>• Introduction of chamber pressure feedback mechanism on the spool dynamics brings backdrivability.</td>
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<td>10:25–10:30</td>
<td>TUA1.6</td>
<td>A Reconfigurable Hybrid Actuator with Rigid and Soft Components</td>
<td>Yaohui Chen, Sing Le, Qiao Chu Tan, Oscar Lau, Chaoyang Song*</td>
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<td></td>
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<td>• A lobster-inspired actuator with both rigid and soft components addressing repeatability, vulnerability, and programmability issues,</td>
<td>Faculty of Engineering, Monash University, Australia</td>
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<td></td>
<td>• Investigation including hybrid actuator design, fabrication and characterization;</td>
<td>Fang Wan</td>
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<td>• Adaptive to object geometry with reconfigurable motion as robotic fingers.</td>
<td>Independent Researcher, China</td>
</tr>
</tbody>
</table>
Scalable Pneumatic and Tendon Driven Robotic Joint Inspired by Jumping Spiders

Alexander Spröwitz, Chantal Göttler, Ayush Sinha, Corentin Caer, Mehmet Ugur Ötzekin, Kirstin Petersen, Metin Sitti
MPI IS Germany, Max Planck ETH CLS, IIT Kanpur India, Horace Mann School USA, METU Turkey, Cornell University USA

Novel pneumatically driven torque joint for segmented robotic legs
Mechanism with perp. contact angle between active area and shell elements
Compact, arc-shaped, nested shell structure and pressure bag design
Experimental validation with dynamic vertical jumps up to 11.5 cm at 58 kPa

Position-Based PD Control Design for Hydraulic Robots Using Passive Subsystems in Multi-time Scales

Woongyong Lee and Wan Kyun Chung
Mechanical Engineering, POSTECH, Republic of Korea

- Conventional hydraulic robots operate without feedback interconnections because the servovalves used in their actuation systems include non-backdrivable mechanisms.
- Virtual internal leakage injected into the system decomposes the hydraulic robot into passive subsystems.
- Stability-guaranteed Position-Based PD controller with inner-loop torque controller enables to interact passively with unexpected environments
Optimization and Optimal Control
Chair Jake Abbott, University of Utah
Co-Chair Yasuhisa Hirata, Tohoku University

Fast Second-order Cone Programming for Safe Mission Planning
Kai Zhong
Inst. for Comp. Eng. and Sci., University of Texas at Austin, USA
Prafull Jain and Ashish Kapoor
Microsoft Research, India and Microsoft Research, USA

- Safe mission control under uncertain environment requires to solve a series of SOCP problems at each time step.
- Traditional interior point methods need to use dynamic libraries.
- Propose a Wolfe-based algorithm exploiting geometry of SOCP carefully.
- Our algorithm is fast and memory-efficient, enabling energy-efficient real-time onboard planning.

Running time (s) comparison among Wolfe’s, projected gradient descent (PGD), cutting plane method (CPM), interior point method (SDPT3)

AN EFFICIENT OPTIMAL PLANNING AND CONTROL FRAMEWORK FOR QUADRUPEDAL LOCOMOTION
Farbod Farshidian, Michael Neunert, Alexander Winkler, Gonzalo Rey, Jonas Buchli
Agile & Dexterous Robotics Lab, ETH Zurich, Switzerland

- Proposing an optimal control framework based on switched system modeling for legged robot locomotion
- Introducing a constrained SQP algorithm as an efficient dynamic programming
- Motion planning and control for centroidal dynamics plus full kinematics of HyQ

Time series of 1m gap crossing using a walking gait on HyQ

A kITE in the Wind: Smooth Trajectory Optimization in a Moving Reference Frame
Vishal Dugar, Sanjiban Choudhury and Sebastian Scherer
Robotics Institute, Carnegie Mellon University, USA

- Smooth, time-optimal trajectory optimization for UAVs in the presence of wind.
- Elegantly decouples path optimization from velocity optimization while ensuring dynamic feasibility.
- Validated with experiments on a full-size autonomous helicopter with real-time wind updates.
- Tested with speeds up to 50m/s in winds up to 20m/s.

Computing Minimum-power Dipole Solutions for Interdipole Forces using Nonlinear Constrained Optimization with Application to Electromagnetic Formation Flight
Jake Abbott and Joseph Brink
Department of Mechanical Engineering, University of Utah, USA
Braxton Osting
Department of Mathematics, University of Utah, USA

- In electromagnetic formation flight (EMFF), spacecraft within a cluster are equipped with controllable magnetic dipoles that are used to control their relative positions by generating interdipole forces.
- This paper presents a method for finding a minimum-power solution to achieve a desired set of forces using sequential quadratic programming.

EMFF scenarios considered in numerical validation experiments, with interdipole spacing indicated
Implicit Robot Force Control based on Set Invariance

Matteo Parigi Polverini, Davide Nicolis, Andrea Maria Zanchettin, and Paolo Rocco
DEIB, Politecnico di Milano, Italy

- The proposed controller ensures set invariance and Lyapunov stability
- No additional stabilizing control law required
- High force reference tracking performance compared to state-of-the-art approaches
- No force overshoots for smooth reference tracking

A new framework for optimal path planning of rectangular robots using a weighted $L_p$ norm

Nak-seung Hyun, Patricio Vela and Erik Verriest
Electrical and Computer Engineering, Georgia Institute of Technology, USA

- Obstacle avoidance path planning for rectangular robots and obstacles in $SE(2)$
- Inspired by a geometry of level sets of weighted $L_p$ norm
- No integer variables are required
- Only logical AND operations are needed to analytically characterize safe configuration
**Growth Measurement of Tomato Fruit based on Whole Image Processing**

Rui FUKUI, TsuRugi NISHIOKA, Shinichi WARISAWA*1 and Ichiro YAMADA  
Graduate School of Frontier Science, the University of Tokyo  
Mechanical Engineering Department, EPFL

- This study tries to estimate the volume of tomato fruits not from fruits individual images but from whole images of tomato plants.
- Our approach is based on features extraction from images using a sub-image clustering technique.
- Images being described as a number of pixel in various labels are used in a regression model to estimate the fruit volume.


Li Liu, Yi Zhou, Ling Shao  
Department of Computing Science, University of East Anglia, UK

- A nature and less-tedious calibration approach is proposed for head-mounted gaze trackers.
- A on-line sparse Gaussian Process method is applied to registering the pupil centers with image gaze point.
- The smooth pursuit identification is designed to identify whether the user is focusing on the calibration point.
- The parallax error is compensated via the virtual affine parallax structure.

**LS-ELAS: Line Segment based Efficient Large Scale Stereo Matching**

Radouane Ait-Jellal and Andreas Zell  
Cognitive systems, University of Tuebingen, Germany  
Manuel Lange, Benjamin Wassermann and Andreas Schilling  
Visual computing, University of Tuebingen, Germany

- We propose a Bayesian approach for dense binocular stereo matching.
- Our prior is based on a set of line segments and a set of support points.
- We use the constrained Delaunay triangulation to generate a triangle mesh which preserves possible depth discontinuities.
- We use this triangle mesh to restrict the search domain to a very small interval.

**A Comparative Analysis of Tightly-coupled Monocular, Binocular, and Stereo VINS**

Mrinal K. Paul, Kejian Wu, and Stergios I. Roumeliotis  
MARS Lab, University of Minnesota, USA  
Joel A. Hesch and Esha D. Nerurkar  
Department of Computer Science & Engineering  
University of Washington, USA

- Deep network learns effect of actions on objects in an environment, from raw depth data.
- Segments environment into objects (without supervision) and predicts SE(3) rigid motions for each distinct object.
- Robust to changes in object properties (size, mass, pose, shape, count) and applied forces.
- Tested on four simulated and one real robot task (Baxter pushing objects on a table).
- Significantly outperforms standard deep baseline.
Probabilistic Articulated Real-Time Tracking for Robot Manipulation

Cristina Garcia Cifuentes, Jan Isaac, Manuel Wüthrich, Stefan Schaal and Jeannette Bohg
Max Planck Institute for Intelligent Systems, Germany

• Precise robot joint state estimation by asynchronous fusion of depth images and angle measurements.
• Robust to time-varying angle bias, inaccurate kinematics, and external occlusions.
• Extensive quantitative evaluation on a challenging new dataset from a real robot.
• We release our code and dataset.

Self-Supervised Visual Descriptor Learning for Dense Correspondence

Tanner Schmidt and Dieter Fox
Computer Science & Engineering, University of Washington, USA
Richard Newcombe
Oculus Research, USA

• KinectFusion and DynamicFusion are used to identify corresponding points within RGB-D videos.
• A fully-convolutional neural network is trained to output features suitable for identifying within-video correspondences.
• Learning to be viewpoint- and lighting-invariant in each video leads to a representation that is consistent across videos.
• No human labels required.
Evaluation of Automated Vehicles in the Frontal Cut-in Scenario
- an Enhanced Approach using Piecewise Mixture Models

Zhiyuan Huang, Ding Zhao, Henry Lam, David J. LeBlanc, Huiyi Peng
University of Michigan, USA

- Accelerated Evaluation of Automated Vehicle
- Model the naturalistic driving data using Piecewise Mixture Distribution
- Cross Entropy method with the Piecewise Mixture Model
- Demonstration in the Frontal Cut-in Scenario

Find Your Own Way: Weakly-Supervised Segmentation of Path Proposals for Urban Autonomy

Dan Barnes, Will Maddern and Ingmar Posner
Oxford Robotics Institute, University of Oxford, UK

- Road scene understanding is critical for autonomous driving, and often relies on clear road markings or expensive manual labelling.
- Using odometry and 3D LiDAR, we generate vast quantities of training data without manual labelling covering lighting, weather and traffic conditions.
- We train a semantic segmentation network to predict the pixel-wise class labels, and at run time we segment proposed paths and obstacles with only a monocular camera.

Ego-Centric Traffic Behavior Understanding through Multi-Level Vehicle Trajectory Analysis

Donghao Xu, Xu He, Huijing Zhao, Jinshi Cui, Hongbin Zha
Key Lab of Machine Perception, Peking University, China
Franck Guillemard, Stephane Geronimi, François Aioun
PSA Peugeot Citroën, France

- We propose a multi-level approach to modeling interactive traffic behaviors based on surrounding vehicle trajectories collected from the ego-centric perspective.
- The approach consists of 3 steps: regional modeling, path discovery and path modeling.
- Experimental results of each step are shown and applications such as local and global anomaly detection and trajectory prediction are demonstrated.

A Model-Predictive Motion Planner for the IARA Autonomous Car

Vinicius Cardoso*, Josias Oliveira*, Thomas Teixeira*, Claudine Badue*, Filipe Mutz*, Thiago Oliveira-Santos*, Lucas Veronese* and Alberto F. De Souza*, Senior Member, IEEE
*Departamento de Informática, Universidade Federal do Espírito Santo, Brazil 
*Coordenação de Informática, Instituto Federal do Espírito Santo, Brazil

- We present a model-predictive motion planner (MPMP) for the IARA autonomous car.
- MPMP computes trajectories that precisely follow a path previously produced by a Human driver at a rate of 20 Hz.
- MPMP is able to follow the path (distances of 0.15 m in average) while smoothly driving IARA at speeds of up to 32.4 km/h (9 m/s).

Vehicle Tracking Using Extended Object Methods: An Approach for Fusing Radar and Laser

Alexander Scheel, Stephan Reuter, and Klaus Dietmayer
Institute of Measurement, Control, and Microtechnology, Ulm University, Germany

- Goal: environment perception for automated vehicles
- Fully probabilistic formulation of the multi-object tracking problem
- Detailed measurement models work with ambiguous sensor data in arbitrary situations
- Filter achieves redundancy and resolves ambiguous situations over time
An Online Probabilistic Intersection Detector

Augusto Luis Ballardini and Daniele Cattaneo and Simone Fontana and Domenico G. Sorrenti
Dept Informatica Sistemistica e Comunicazione, Università degli Studi di Milano-Bicocca, Italy

- We propose an online probabilistic approach for detecting and classifying urban road intersections
- We rely on a geometric detection of the road ground plane and on a pixel-level classification
- Temporal coherence between consecutive frames is achieved by means of a probabilistic scheme
- We validate our system on challenging residential sequences from the KITTI dataset

Risk Assessment for Automatic Lane Change Maneuvers on Highways

Samyeul Noh and Kyoungwan An
Intelligent Robotics Research Division, Electronics and Telecommunications Research Institute (ETRI), Republic of Korea

- Capable of reliably assessing a given highway situation in terms of the possibility of collisions
- Capable of robustly giving a recommendation for lane changes
- Evaluated on a closed high-speed test track in simulated traffic through in-vehicle testing
- Evaluated on public highways in real traffic through in-vehicle testing

Experimental results on public highways
**Detachable Modular Robot capable of Cooperative Climbing and Multi Agent Exploration**

Sri Harsha Turlapati, Ankur Srivastava and K. Madhava Krishna  
Robotics Research Center, IIIT Hyderabad, India  
Dept. Of Mechanical Engineering, IIT Jodhpur, India

- At the intersection of Multi Agent Systems and Uneven Terrain Navigation  
- Capable of collaborative climbing and distributed exploration  
- Robot task scheduling incorporating design considerations in MAS optimization  
- Manually controlled  
- Obstacle/Stair Climbing, Tight space navigation

**Formation of differential-drive vehicles with field-of-view constraints for enclosing a moving target**

Gonzalo Lopez-Nicolas  
Universidad de Zaragoza - I3A, Spain  
Miguel Aranda and Youcef Mezouar  
Institut Pascal, UCA-SIGMA-CNRS, Clermont-Ferrand, France

- Context: Enclose and track a moving target within a desired formation.  
- Goal: Full perception of the target with the vision sensors onboard the robots.  
- Problem: Overcome differential-drive motion constraints and cameras with limited field of view.  
- Contribution: Formation trajectories to enclose and track the target while respecting the constraints.

**Safe Decentralized and Reconfigurable Multi-Agent Control with Guaranteed Convergence**

C. Vrohidis, C. P. Bechlioulis and K. J. Kyriakopoulos  
Control Systems Lab, School of Mechanical Engineering, National Technical University of Athens, Greece

- Leader – Follower scheme in cluttered environment;  
- Formation specifications;  
- Discrete connectivity-preserving reconfiguration algorithm;  
- Overall control scheme guarantees convergence to the desired configuration.

**Distributed Multi-Robot Coordination for Dynamic Perimeter Surveillance in Uncertain Environments**

Alexander Jahn1, Reza J. Alitappeh2, David Saldaña3, Luciano C. A. Pimenta1,4, Andre G. Santos2, Mario F. M. Campos3  
1PPGEE, UFMG, Brazil  
2Computer Science, UFV, Brazil  
3VeRLab, UFMG, Brazil  
4National Institute of Science and Technology for Cooperative Autonomous Systems Applied to Security and Environment, Brazil

- Multi-agent system creating a virtual fence for escort missions in a partially known environment  
- The formation can deform and adapt to the environment  
- Decentralized, cooperative path-planning based on RRT  
- Decentralized controller that uses only local information

**Distributed Data Gathering with Buffer Constraints and Intermittent Communication**

Meng Guo and Michael M. Zavlanos  
Computer Science, UFV, Brazil  
1,4, Reza J. Alitappeh2, David Saldaña3, Luciano C. A. Pimenta1,4, Andre G. Santos2, Mario F. M. Campos3

- Local data-gathering tasks as LTL formulas.  
- Limited communication radius.  
- Limited buffer to save data.  
- Inter-robot data transfer via intermittent communication.  
- Guaranteed satisfaction of all local tasks.  
- Efficiency over all-time connectivity.

**Decentralized Multiagent Collision Avoidance with Deep Reinforcement Learning**

Yu Fan Chen, Miao Liu, Michael Everett, and Jonathon P. How  
Aero&Astro, Massachusetts Institute of Technology, USA

- Autonomous indoor navigation often requires operating alongside other dynamic agents with unknown intents (goals) and policies.  
- Used deep reinforcement learning to develop a policy that accounts for uncertainty in other agents’ motion.  
- Achieved 26% improvement in path quality (time to reach goal) compared with GRCA  
- Demonstrated efficient, real-time performance on ground robots.

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2017 IEEE International Conference on Robotics and Automation
Decentralized Matroid Optimization for Topology Constraints in Multi-Robot Allocation Problems

Ryan Williams
Department of Electrical and Computer Engineering, Virginia Tech, USA
Andrea Gasparri and Giovanni Ulivi
Department of Engineering, Roma Tre University, Italy

- Topological and abstract task constraints in allocation problems by applying the combinatorial theory of matroids.
- Problems modeled as an intersection of matroid constraints, achieving arbitrary combinatorial relationships in allocation space.
- Coupling abstract per-robot constraints with a communication spanning tree constraint; provable suboptimality with greedy algorithm.
- Decentralized algorithm described that applies auction methods to task allocation with matroid intersections.

Task allocation with topology constraints

Formations for Resilient Robot Teams

Luis Guerrero-Bonilla, Amanda Prorok and Vijay Kumar
GRASP Laboratory, University of Pennsylvania, United States of America

- Asymptotic consensus in the presence of malicious agents can be achieved by imposing a set of conditions, known as "r-robustness", on the graph describing the communication among the robots in a team.
- Our work presents algorithms to construct r-robust graphs, given the number of robots and the number of malicious agents among them.
- The constructed graphs can be used to specify resilient formations of robots.

A 3-robust graph with 5 robots
Learning Task Constraints in Operational Space Formulation

Hsiu-Chin Lin
School of Informatics, University of Edinburgh, United Kingdom
Prabhat Ray and Matthew Howard
Department of Informatics, Kings College London, United Kingdom

• How should constraints be imposed in order to adapt a control policy to a new constrained movement?
• The problem is formulated into an operational space control framework.
• The proposed method estimates the constraint matrix from observed movement in absence of any prior knowledge.
• The approach has been demonstrated on the AR-10 Robotic Hand performing manual operations.

Learning Multimodal Models for Robot Dynamics Online with a Mixture of Gaussian Process Experts

Christopher McKinnon and Angela P. Schoellig
Institute for Aerospace Studies, University of Toronto, Canada

• Learning a multimodal system model from data using Gaussian Processes in a Dirichlet Process mixture model.
• Automatically learns a new model when a new and distinct operating condition is encountered.
• Enables a robot to re-use past experiences from an arbitrary number of previously visited operating conditions.
• Demonstrated in experiment on a ground robot.

Learning from the Hindsight Plan -- Episodic MPC Improvement

Aviv Tamar, Garrett Thomas, Tianhao Zhang, Sergey Levine, Pieter Abbeel
EECS Department, UC Berkeley

• Learn to improve MPC control in iterative (episodic) tasks.
• After each episode, re-compute the MPC control in hindsight, with a longer planning horizon (offline).
• Learn neural network cost shaping for online MPC that mimics the hindsight plan.
• Evaluation on robotic manipulation domains.

Autonomous Interpretation of Demonstrations for Modification of Dynamical Movement Primitives

Martin Karlsson, Anders Robertsson and Rolf Johansson
Dept. Automatic Control, Lund University, Sweden

• Modification of dynamical movement primitives (DMPs) using lead-through programming.
• Convex optimization to automatically merge existing DMP with corrective demonstration.
• Offers quick modification, without engineering work.
• Real-time application was implemented and verified experimentally.

High-Precision Tracking in Changing Environments Through $\zeta_1$ Adaptive and Iterative Learning

Karime Pereida, Rikky R. P. R. Duivenvoorden and Angela P. Schoellig
Institute for Aerospace Studies, University of Toronto, Canada

• In unknown and dynamic environments, controllers must cope with disturbances, unmodeled dynamics and parametric uncertainties.
• We propose a framework combining $\zeta_1$ adaptive control and iterative learning.
• Experimental results show significant improvements in learning convergence and robustness to changing system dynamics.
A Systematic Approach for Minimizing Physical Experiments to Identify Optimal Trajectory Parameters for Robots

Ariyan M. Kabir\textsuperscript{1} and Joshua D. Langsfeld\textsuperscript{2} and Cunbo Zhuang\textsuperscript{2} and Krishnandan N. Kaipa\textsuperscript{3} and Satyandra K. Gupta\textsuperscript{1}

\textsuperscript{1}Center for Advanced Manufacturing, University of Southern California, CA USA,
\textsuperscript{2}Maryland Robotics Center, University of Maryland, MD USA
\textsuperscript{3}Dept. of Mechanical and Aerospace Engineering, Old Dominion University, VA USA

- Minimize number of experiments to optimize operation parameters
- Enable automation of non-repetitive tasks such as robotic cleaning
- Constrained optimization problem for known objective function with black-box constraints
- Probabilistic decision making based on uncertainty in surrogate models

Comparing Human-Centric and Robot-Centric Sampling for Robot Deep Learning from Demonstrations

Michael Laskey, Caleb Chuck, Jonathan Lee, Jeffrey Mahler, Sanjay Krishnan, Kevin Jamieson, Anca Dragan and Ken Goldberg
EECS and IEOR, UC-Berkeley, USA

- We compared to different types of LfD algorithms Human-Centric (HC) and Robot-Centric (RC)
- We found that despite the theoretical advantages of RC, HC methods performed better with human supervisors.
- We provide a post analysis that offers new insights into the difference between RC and HC
Multi-label Tactile Property Analysis

Huaping Liu, Yupei Wu, Fuchun Sun, Di Guo, Bin Fang
Department of Computer Science and Technology, Tsinghua University
State Key Lab. of Intelligent Technology and Systems, Beijing, China

- A novel multi-label dictionary learning framework is established for tactile property recognition.
- A globally convergent iterative algorithm is developed to solve the dictionary learning problem.
- Experimental validations on the public available tactile property dataset are performed to show the advantages of the proposed method.

Reliable object handover through tactile force sensing and effort control in the Shadow Robot hand

Augusto Gómez-Eguíluz and Inaki Rano
and Sonya Coleman and Martin McGinnity
Intelligent Systems Research Centre, Ulster University, UK

- Robot-Human Object Handover system using the Shadow Robot hand.
- Contact force estimation using BioTAC tactile sensor.
- The system guarantees the safety of both the robot and the object during the handover.
- A grasp effort controller provides adaptation against pose object perturbations.
- Releases only when the receiver pulls from the object.

Touch Based Localization
For High Precision Manufacturing

Brad Saund, Shiyuan Chen, and Reid Simmons
Robotics Institute, Carnegie Mellon, USA

- Autonomous localization of objects from CAD with an emphasis in manufacturing environments
- Particle filter using rejection sampling and precomputed distance field
- Information gain as a discrete decision process over particles

Passivity-based Stability in Explicit Force Control of Robots

Ribin Balachandran and Jordi Artigas
German Aerospace Center (DLR), Germany
Mikael Jorda and Oussama Khatib
Robotics Lab, Stanford University, USA
Jee-Hwan Ryu
BioRobotics Lab, Koreatech, Republic of Korea

- A step-by-step procedure to stabilise explicit force control by deriving:
  - Signal flow diagram
  - Electrical circuit diagram
  - 2-port representation
  - Energy analysis and passivisation using Time Domain Passivity Control
- This procedure can be followed in other control methods as well.

Efficient Event-Driven Reactive Control for Large Scale Robot Skin

Florian Bergner, Emmanuel Dean-Leon and Gordon Cheng
Technical University of Munich, Germany

- New event-driven reactive skin controller reduces CPU usage by 66% in comparison to synchronous reference controller
- Comprehensive performance evaluation with our robot TOMM

Skin Normal Force Calibration Using Vacuum Bags

Joan Kangro, Silvio Traversaro, Daniele Pucci, Francesco Nori
Dynamic Interaction Control, Istituto Italiano di Tecnologia, Italy

- Pressure in the bag is lowered => induces uniform pressure distribution
- Capacitance values for each sensor and pressure value are extracted during calibration
- Each sensor is modelled as:
  \[ \mathbf{R}(C) = a_0 + b_0 C_t + c_0 C_t^2 + d_0 C_t^3 + e_0 C_t^4 + f_0 C_t^5 \]
- The calibration takes 1-2 minutes and can be applied to a variety of skin shapes
### Force and Tactile Sensing I

Chair Gordon Cheng, Technical University Munich  
Co-Chair Francesco Nori, ISTITUTO ITALIANO DI TECNOLOGIA

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<th>Session</th>
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| 10:25–10:30 | TUA7.7  | A Highly Sensitive Multimodal Capacitive Tactile Sensor             | Thuy-Hong-Loan Le, Alexis Maslyczyk, Jean-Philippe Roberge, and Vincent Duchaine  
Command and Robotics Laboratory (CoRo),  
École de Technologie Supérieure, Montreal, Canada | • Highly sensitive multimodal capacitive tactile sensor  
• Static and dynamic sensing are integrated in the same layer of the capacitive sensor  
• Improvements in both mechanical and electrical design, simplifying the manufacture process  
• Large range of force sensing and be able to detect contact events  
Sensors mounted on Robotiq gripper                                                                                                                                                      |
| 10:30–10:35 | TUA7.8  | Incipient Slip Detection and Recovery for Controllable Gecko-Inspired Adhesion | X. Alice Wu 1, David L. Christensen 1, Srinivasan A. Suresh 1, Hao Jiang 1, William R. T. Roderick 1, and Mark Cutkosky 1  
1Mechanical Engineering, Stanford University, USA | • We present work on incipient slip sensing and recovery for controllable gecko-inspired adhesives.  
• Using signals from an on-board tactile sensor, we detect the onset of adhesive failure and execute recovery behavior.  
• The system using tactile sensor feedback is able to achieve >92% of the peak adhesion performance.  
• Results consistent over a variety of common smooth surfaces, with the system achieving repeatable force loading independent of materials and surface conditions.  
A μTug micro-robot with integrated tactile sensing is able to maximize its pulling capability using force feedback.                                                                 |
**Effects of Discretization on the K-Width of Series Elastic Actuators**

Dylan P. Losey and Marcia K. O’Malley

Mechanical Engineering, Rice University, USA

- K-Width refers to the range of virtual stiffness that an SEA can safely render
- Discretization introduced by the computer interface influences the K-Width of SEAs
- We derive an equation for the K-Width of SEAs when considering this discretization
- The K-Width can be increased by adding damping or increasing the sampling rate

**Blindfolded Robotic Teleoperation using Spatial Force Feedback to the Toe**

Annette Hagengruber and Hannes Höppner

and Jörn Vogel

Institute of Robotics and Mechatronics, German Aerospace Center (DLR), Wessling, Germany

- 12 subjects teleoperated a DLR Light-Weight Robot in a blindfolded task
- A three-dimensional spatial force to the toe was the only available feedback
- The forces reflected the contact forces at the robotic end-effector
- Subjects could successfully finish the task in more than two-thirds of all trials

**On the Passivity of Mechanical Integrators in Haptic Rendering**

Myungsin Kim, Juhyeok Kim, Yongjun Lee, and Dongjun Lee

Department of Mechanical & Aerospace Engineering and IAMD, Seoul National University, Republic of Korea

- We propose a novel haptic rendering framework based on Passive Midpoint integrator (PMI)
- Passive rendering of articulated rigid bodies in SE(3) and multipoint contact problem are addressed
- Stable simulation stiff systems and lossless harmonic oscillation with slow update-rate are achieved

**WRAP: Wearable, Restricted-Aperture Pneumatics for Haptic Guidance**

Michael Raitor, Julie M. Walker, Allison M. Okamura, and Heather Culbertson

Department of Mechanical Engineering, Stanford University, U.S.A.

- Developed a novel haptic actuator using pressurized air
- Defined actuator design and fabrication constraints
- Demonstrated effectiveness of actuator for identification of direction cues through a user study
- Established versatility of actuator through two additional demonstrations of use cases: ultrasound probe guidance and computer mouse guidance

**Proton 2: Increasing the Sensitivity and Portability of a Visuo-haptic Surface Interaction Recorder**

Alex Burka, Abhinav Rajvanshi, Sarah Allen, and Katherine J. Kuchenbecker

MEAM, ESE, CIS Departments, GRASP Lab, University of Pennsylvania, USA

- Developed a novel haptic actuator using pressurized air
- Defined actuator design and fabrication constraints
- Demonstrated effectiveness of actuator for identification of direction cues through a user study
- Established versatility of actuator through two additional demonstrations of use cases: ultrasound probe guidance and computer mouse guidance

**A Practically Linear Relation between Time Delay and the Optimal Settling Time of a Haptic Device**

Thomas Hulin

German Aerospace Center (DLR), Germany

- The optimal settling time of a haptic device depends practically linearly on time delay
- Hence, a rule of thumb is introduced to predict the optimal performance of a haptic device
- Each sampling period of additional time delay causes the optimal settling time to increase by approximately five sampling periods
- The effect of discrete-time sampling appears to correspond to a delay of one whole sampling period
Collision Representation Using Vibrotactile Cues to Bimanual Impact Localization for Mobile Robot Operations

Daniel Gongora¹, Hikaru Nagano¹, Yosuke Suzuki², Masashi Konyo¹ and Satoshi Tadokoro¹
¹Graduate School of Information Sciences, Tohoku University, Japan
²Institute of Science and Engineering, Kanazawa University, Japan

- Impact vibrations of an object held with both hands can be used to estimate the impact point.
- Two vibrotactile cues to bimanual impact localization are differences in amplitude and duration between hands.
- In simple teleoperated tasks, completion time is likely to benefit from vibrotactile collision feedback.

Variable Damping Force Tunnel for Gait Training Using ALEX III

Paul Stegall
Department of Mechanical Engineering, University of Pennsylvania, USA

Damiano Zanotto
Department of Mechanical Engineering, Stevens Institute of Technology, USA

Sunil Agrawal
Department of Mechanical Engineering, Columbia University, USA

- Haptic field where damping coefficient increases with error
- Descriptive feedback
- Higher rates of change in the damping coefficient produced greater adaptation
Past, Present, and Future of Simultaneous Localization And Mapping: Towards the Robust-Perception Age

Cesar Cadena1, Luca Carlone2, Henry Carrillo3, Yasir Latif4, Davide Scaramuzza5, José Neira6, Ian Reid4, John J. Leonard7

1Autonomous Systems Lab, ETH Zurich, Switzerland.
2Laboratory for Information and Decision Systems, MIT, USA.
3Esc. de Ciencias Exactas e Ing., U. Sergio Arboleda, Colombia.
4School of Computer Science, University of Adelaide, Australia.
5Robotics and Perception Group, U. of Zürich, Switzerland.
6D. de Informática e Ing. de Sistemas, U. de Zaragoza, Spain.
7Marine Robotics Group, MIT, USA.

Survey and our views for the future of:

- Long-term Autonomy
- Robustness
- Scalability
- Representation
- Metric Map Models
- Semantic Map Models
- New Theoretical Tools for SLAM
- Active SLAM
- New Frontiers: Sensors and Learning

Optimal Multi-Robot Path Planning on Graphs: Complete Algorithms and Effective Heuristics

Jingjin Yu
Department of Computer Science, Rutgers University, USA
Steven M. LaValle
Department of Computer Science, University of Illinois, USA

- Algorithms for optimal or near-optimal multi-robot path/motion planning on graphs
- Based on network flow and ILP
- Supports common objectives
  - Minimum makespan
  - Minimum total time
  - Minimum maximum distance
  - Minimum total distance
- High performance

Rapidly-exploring Random Cycles: Persistent Estimation of Spatiotemporal Fields

Xiaodong Lan
Mechanical Engineering, Boston University, USA
Mac Schwager
Aeronautics and Astronautics, Stanford University, USA

- Proposed RRC and RRC* to plan periodic trajectories to estimate spatiotemporal field.
- RRC and RRC* are monotonic.
- RRC and RRC* are efficient in high dimensional configuration space.
- Applied RRC and RRC* to plan periodic trajectories to estimate ocean temperature in Caribbean Sea.

Sequential Action Control: Closed-Form Optimal Control for Nonlinear and Nonsmooth Systems

Alex Ansari and Todd Murphey
Mechanical Engineering, Northwestern University, United States

- Sequential Action Control (SAC) is closed form for general nonlinear and nonsmooth systems
- It is model predictive and often coincide with optimizers obtained using iterative optimization
- SAC obtains results at least as good as best known in literature for numerous benchmarks, and can be easily implemented for a broad range of systems
A Rehabilitation Exercise Robot for Treating Low Back Pain

Wonje Choi, Jongseok Won, Hyunbum Cho and Jaeheung Park
Graduate School of Convergence Science and Technology, Seoul National University, Republic of Korea

- Low back pain is one of the world's most serious health problems.
- The “big 3” exercises proposed by McGill were designed based on scientific evidence.
- SERA is a robot that helps the big 3 exercise for vulnerable patients.
- The SEA of the robot makes it possible to adjust the exercise load by applying anti-gravity force to the necessary part on the body.

A 3 Wire Body Weight Support System for a Large Treadmill

Pouya Sabetian
Department of Mechanical Engineering, University of Utah, USA
John M. Hollerbach
The School of Computing, University of Utah, USA

- A 3 Wire Body Weight Support (BWS) System has been developed to span over a large treadmill.
- The BWS system can span the workspace while applying constant unloading force and close to zero forces horizontally on the user.
- Some of BWS applications are locomotion rehabilitation for patients with neurological problems, reduced gravity display, and steep slope display.

Design and Validation of a Multi-Axis Robotic Platform for the Characterization of Ankle Neuromechanics

Varun Nalam and Hyunglae Lee
School for Engineering of Matter, Transport, and Energy, Arizona State University (ASU), USA

- Presents the design and validation of a robotic platform for the characterization of ankle neuromechanics: mechanical impedance and reflex responses of the ankle.
- Demonstrates the platform’s capability of providing highly accurate position perturbations, simulating various mechanical (haptic) environments, and eliciting stretch reflex responses of the ankle muscles.

A Novel Framework for Optimizing Motor (Re)-learning with a Robotic Exoskeleton

Priyanshu Agarwal and Ashish D. Deshpande
Mechanical Engineering Department, University of Texas at Austin, USA

- We present a framework for robot-assisted motor (re)-learning for providing subject-specific training.
- Framework allows for simultaneous adaptation of task, assistance and feedback based on the performance of the subject during the task.
- Results from a pilot study suggested that training under simultaneous adaptation affects motor learning significantly.

Design and Validation of a Torque Dense, Highly Backdrivable Powered Knee-Ankle Orthosis

H. Zhu1,2, J. Doan1,2, C. Stence1,3, G. Lv1,2, T. Elery1,3, R. Gregg1,3
1 Bioengineering, 2 Electrical and Computer Engineering, 3 Mechanical Engineering, The University of Texas at Dallas, USA

- Precise torque control and backdrivability without series elastic components.
- High output torque without a high-ratio transmission.
- Light weight and compact actuation system.

A robotic orthosis with a cable-differential mechanism

Jaehwan Park, Seunghan Park, Chan Ho Park, Seungmin Jung, Chankyu Kim, and Junho Choi
Center for Bionics, Korea Institute of Science and Technology, S. Korea
Jong Hyeon Park
Mechanical Engineering, Hanyang University, S. Korea

- A robotic orthosis for stroke patient, which is worn at the affected side of the patient
- Cable-differential mechanism is used for power transmission
- Actuators are located at the base to reduce inertia of the orthosis
- Actuator loads are shared by two actuators using the cable-differential mechanism, which makes smaller actuator to be used
Stability of the Human Ankle in Relation to Environmental Mechanics

Harrison Hanzlick, Hunter Murphy and Hyunglae Lee
School for Engineering of Matter, Transport, and Energy,
Arizona State University (ASU), USA

- Characterizes lower bound of ankle stability in stiffness-defined haptic environment in two DOF.
- Simple settling time analysis quantifies trends between ankle stability and environmental stiffness.
- Provides essential information for the design of controllers for physically-interactive robots.

Learning by Demonstration for planning activities of daily living in rehabilitation and assistive robotics
Clemente Lauretti1, Francesca Cordella1, Eugenio Guglielmelli1 and Loredana Zollo1
1Laboratory of Biomedical Robotics and Bioinsystems, Campus Bio-Medico University, Rome, Italy

- A motion planning system for rehabilitation and assistive robotics is proposed.
- It is grounded on a combination of Learning by Demonstration and Dynamic Movement Primitives.
- The theoretical formulation has been described and a comparative analysis with the literature has been performed.
- An experimental validation on eight healthy subjects has been carried out during three activities of daily living with the robot assistance.
Static and Dynamic Partitions of Inequalities and Their Application in Supervisor Simplification

Chen Chen and Hefei Hu
School of EMME, Xi’an University, China
Yang Liu
School of SCNF, NTU, Singapore

• First, static partition divides linear inequalities into independent and dependent ones based on the analysis of theoretically admissible markings. An independent inequality is always dependent on the independent ones. This is the meaning of “static”.
• Second, dynamic partition separates inequalities into active and inactive ones based on analysis of actually admissible markings. An inequality may be active in a current system but can become an inactive one in the augmented system where some specifications have been enforced. This is the meaning of “dynamic”.
• The dynamically active inequality is also a statically independent one, but not vice versa. And the statically dependent inequality is also a dynamically inactive one, but not vice versa.
• Static partition does not require any system information while dynamic one does. They together can complementarily explain many simplification principles.

Constraint-based Sample Propagation for Improved State Estimation in Robotic Assembly

Korbinian Nottensteiner, Katharina Hertkorn
Institute of Robotics and Mechatronics (RMC-RM), German Aerospace Center (DLR), Germany

• Observation of robotic assembly tasks with non-fixed parts in the workcell, e.g. sliding motion on table surface.
• Constraint-based sample propagation in state estimation using a sequential Monte Carlo approach.
• Experimental validation in a dual arm robot setup, in which one of the arms is used to simulate the motion of the sliding part in the environment.

CoSTAR: Instructing Collaborative Robots with Behavior Trees and Vision

Chris Paxton, Andrew Hundt, Felix Jonathan, and Gregory D. Hager
Department of Computer Science, JHU, USA

• CoSTAR is a modular, cross-platform architecture for authoring robot task plans based on Behavior Trees.
• It allows ordinary end users to quickly author plans with a wide variety of different capabilities.
• It allows us to integrate perception, planning, and simple reasoning into a unified framework.
• CoSTAR won the 2016 KUKA Innovation Award, and source code is available online.

Planning Cuts for Mobile Robots with Bladed Tools

Jeffrey Lipton and Daniela Rus
CSAIL, MIT, USA
Zachary Manchester
SEAS, Harvard University, USA

• Bladed tools in material can be modeled as modified Reeds-Shepp cars
• Unique path following constraints of blades lead to unique solutions.
• By decomposing the path into sections based on closure and curvature, we can find solutions.
• We built a mobile robot with a jigsaw that can cut materials using this algorithm.

Error Robust and Efficient Assembly Sequence Planning with Haptic Rendering Models

Robert Andre and Ulrike Thomas
Robotics and Human Machine Interaction Lab
Technical University of Chemnitz, Germany

• Anytime optimized assembly sequence planning for rigid and non-rigid assemblies using Haptic Rendering Models (HRMs).
• HRMs obtained from CAD-data, only.
• Automatic model analysis and scaling of HRMs to handle inconsistent meshes and parts of various sizes.
• Applies a strategy for automatic disassembly computation.
• Multi-goal optimization on AND/OR graphs for assembly sequence planning.
Self-folded Soft Robotic Structures with Controllable Joints
Cynthia Sung, Rhea Lin, Sangbae Kim, Daniela Rus
Massachusetts Institute of Technology, USA
Shuhei Miyashita
University of York, UK
Sehyuk Yim
Korea Institute of Science and Technology, Korea

- Rapid fabrication technique creates complex compliant structures that are self-assembled and actuated in a few hours
- Algorithms for designing and modeling structures fabricated using this technique
- Experimental verification through three fabricated static structures
- Two end-to-end examples demonstrating design, fabrication, and actuation

Automatic Virtual Metrology and Target Value Adjustment for Mass Customization
H. Tieng, C.-F. Chen, F.-T. Cheng
INST OF MEG INF & SYS, NCKU, Tainan, Taiwan
H.-C. Yang
INST. OF EE, NKFUST, Kaohsiung, Taiwan

- Core Values of Industry 4.0: people, products, and system
- Target Value Adjustment (TVA) + Automatic Virtual Metrology (AVM)
- Illustrative examples of Wheel Machining Automation and Semiconductor Etching
- Process are adopted for demonstrating the versatility of the AVM-plus-TVA approach
A New Design Concept of Magnetically Levitated 4 Pole Hybrid Mover Driven by Linear Motor

Mirsad Bucak, Ahmet Fevzi Bozkurt, Kadir Erkan and Hüseyin Üvet
Mechatronic Engineering Department, Yıldız Technical University, TURKEY

- A new concept of magnetically levitated conveyor system
- Zero power control algorithm for efficiency
- Linear motor modelling and controller design
- Simulations and experimental results of proposed design with algorithms.

Soft Sheet Actuator Generating Traveling Waves Inspired by Gastropod’s Locomotion

Masahiro Watanabe and Hideyuki Tsukagoshi
Department of Mechanical and Control Engineering, Tokyo Institute of Technology, Japan

- Soft sheet actuator capable of generating traveling waves, moving, and carrying is presented.
- Multiple traveling waves can be generated by pneumatics supplied from only three lines.
- It can also pass through even narrow and curved gap, while adapting its own shape to the environment.

Modified Nonlinear Pressure Estimator of Pneumatic actuator for force controller design

Yun-Pyo Hong, Soohyun Kim and Kyung-Soo Kim
Division of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Republic of Korea

- A modified nonlinear pneumatic model for pneumatic force servo systems is proposed.
- By adopting flow coefficient maps, the estimations of pressures are conducted.
- The simulated and experiment data are compared and results show its accuracy compared to a conventional model.
- The applicability of the proposed model to model-based controller design is also shown through the experiment of force servo controls

Magneto-Rheological Linear Clutch for Force Controlled Human Safe Applications

Achu Wilson, Sastra Robotics India Pvt Ltd

- Hand system with high-efficiency electro-hydrostatic actuators (EHA) cluster and low friction tendon guidance.
- Discussion on energy loss in an EHA and design improvement in the hydraulic system.
- Forearm and wrist structure without any sliding contact between tendons and structure.

Pneumatic Reel Actuator: Design, Modeling, and Implementation

Zachary Hammond, Nathan Usevitch, Elliot Hawkes, and Sean Follmer
Mechanical Engineering, Stanford University, USA

- The Pneumatic Reel Actuator (PRA) is highly extensible, lightweight, capable of operating in compression and tension, compliant, and inexpensive
- Extension ratio greater than 16:1
- Force-to-weight ratio of 28.3:1
- Speed of 0.89 meters per second

(A) The PRA in its contracted form and (B) the reel mechanism.
Deep Reinforcement Learning for Tensegrity Robot Locomotion

Marvin Zhang*, Xinyang Geng*, Jonathan Bruce*, Ken Caluwaerts, Massimo Vespignani, Vytas SunSpiral, Pieter Abbeel, Sergey Levine
UC Berkeley, UC Santa Cruz, Autodesk, NASA Ames, OpenAI, ICSI

- Tensegrity robots have a number of appealing properties but are difficult to control
- We automatically learn a locomotion gait for the SUPERball tensegrity robot (right) using mirror descent guided policy search
- Our simulation results show that our learned policies are more efficient than hand-designed open-loop policies and generalize to various environmental and system conditions
- Our real robot results demonstrate the first continuous, reliable locomotion for SUPERball

Development of Giacometti Arm with Balloon Body

Masashi Takeichi
Department of Mechanical Engineering, Tokyo Institute of Technology, Japan
Koichi Suzumori, Gen Endo, and Hiroyuki Nabae
Graduate major in Mechanical Engineering, Tokyo Institute of Technology, Japan

- A prototype of a 7-m-long cantilever arm is designed, developed, and tested
- It is designed to be essentially safe even if it falls down or hits something
- It is expected to be used for inspection during the early stage of disasters
- It is realized using helium-filled balloon bodies and thin pneumatic muscles

The SUPERball tensegrity robot. We learn a rolling gait from scratch for this robot with our algorithm.

Prototype of 7-link arm (7m, 340g, 7DOF)
T-LQG: Closed-Loop Belief Space Planning via Trajectory-Optimized LQG
Mohammadhussein Rafieisakhaei\textsuperscript{1,}\textsuperscript{2}, Suman Chakravorty\textsuperscript{1,}\textsuperscript{3} and P. R. Kumar\textsuperscript{1,}\textsuperscript{3}
\textsuperscript{1}Electrical and Computer Engineering, \textsuperscript{2}Aerospace Engineering Texas A&M University, USA
\textsuperscript{3}Department of Aerospace Engineering, KAIST, Daejeon, Korea

- We reduce the dimension of the general belief space planning problem from \((n\times n^3)\) to \(n\).
- In contrast to previous methods, we do this in the space of closed-loop policies.
- We pose a coupled design of the underlying trajectory of the LQG and the estimator as a nonlinear program.
- We use the separation principle to keep the design of the controller separate from the estimator.

Approximately Optimal Continuous-Time Motion Planning and Control via Probabilistic Inference
Mustafa Mukadam, Ching-An Cheng, Xinyan Yan, and Byron Boots
Institute for Robotics and Intelligent Machines, Georgia Tech, USA

- We provide an efficient algorithm, PIPC, that solves the problem of simultaneous planning and control by providing approximately optimal policies.
- PIPC can consider arbitrary higher-order nonlinear performance indices and scales only linearly in them.
- Efficiency results form a probabilistic interpretation of the problem and Gaussian process representation of trajectories.
- PIPC can handle partially observable linear stochastic systems in dynamic environments.

The Time-Optimal Path Parameterization Problem with Third-Order Constraints
Hung Pham and Quang-Cuong Pham
School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

- The Time-Optimal Path Parameterization problem (TOPP) with third-order constraints has as its optimal solutions profiles following a max-min-max structure.
- Frequently, there are third-order singularities which cause algorithm failures.
- This work presents an analysis and proposes a treatment for third-order singularities.

Real-Time Distributed Receding Horizon Motion Planning and Control for Mobile Multi-Robot Dynamic Systems
José M. Mendes Filho\textsuperscript{a,b}, Eric Lucet\textsuperscript{c} and David Filliat\textsuperscript{b}
\textsuperscript{a}CEA, LIST, Interactive Robotics Laboratory, France
\textsuperscript{b}U2IS, Inria FLOWERS team, Université Paris-Saclay, France

- Distributed Receding Horizon Motion Planning (DRHMP) approach is used to perform kinodynamic planning for multi-robot system.
- Stabilization of unicycle-like vehicles’ state around the planned trajectory is accomplished by a modified nonlinear model predictive control (NCGPC-M).
- Results found in simulation indicate that this approach can be applied to systems subjected to real-time constraints.

The Multi-scale Abstraction, Planning and Control Using Diffusion Wavelets for Stochastic Optimal Control Problems
Jung-Su Ha and Han-Lim Choi
Department of Aerospace Engineering, KAIST, Daejeon, Korea

- This work presents a multiscale framework to solve the stochastic optimal control problems.
- Hierarchical abstraction is obtained from the robot dynamics via diffusion wavelet method.
- Using hierarchy, a global plan with coarse resolution and a detailed local plan for important regions are computed.
- Natural/sophisticated trade-off between the optimality and the computational cost can be exploited.
Differential Dynamic Programming with Nonlinear Constraints

Zhaoming Xie¹  Karen Liu²  Kris Hauser³
1. School of Electrical and Computer Engineering, Georgia Tech, USA
2. School of Interactive Computing, Georgia Tech, USA
3. Department of Electrical and Computer Engineering, Duke University, USA

- New formulation of DDP that accommodates arbitrary nonlinear inequality constraints.
- Derivation of a recursive quadratic approximation formula in the presence of nonlinear constraints.
- Demonstration on several underactuated optimal control problems.

SLIP-model-based Dynamic Gait Generation in a Leg-wheel Transformable Robot with Force Control

Yun-Meng Lin, Hung-Sheng Lin, and Pei-Chun Lin
Department of Mechanical Engineering, National Taiwan University, Taiwan

- Trajectories based on the SLIP model are applied on the robot to initiate trotting and pronking gait behaviors.
- Each leg-wheel of TurboQuad has one rotational DOF and one translational DOF.
- The SLIP-like spring effect of the leg-wheel is achieved using force control with motor current feedback.
- Four different dynamic behaviors with variations in stiffness and gait are tested.
Visibility Enhancement for Underwater Visual SLAM based on Underwater Light Scattering Model

Younggun Cho and Ayoung Kim
Civil and Environmental Engineering, KAIST, South Korea

- The underwater images are often critically degraded by poor atmospheric conditions
- Conventional approaches fail on grayscale images and have a long computational time that is impractical
- The proposed algorithm presents the online image enhancement method with complex model (e.g. light bias, blur, and haze)
- The ultimate objective of the method is to implement it in the visual SLAM pipeline with real-time performance

Reconstructing Vehicles From a Single Image: Shape Priors for Road Scene Understanding

J. Krishna Murthy, G.V. Sai Krishna, Falak Chhaya, and K. Madhava Krishna
Robotics Research Center, KICS, Hyderabad, India

- Recover the shape and pose of a vehicle, given a single (RGB) image.
- Use object category-specific shape priors to do so.
- But, the problem is ill-posed. So, we present a way to decompose the original problem into subproblems which leads to a fast and efficient solution.
- State-of-the-art results on the KITTI object dataset.

Robustifying Correspondence Based 6D Object Pose Estimation

Antti Hietaanen, J.-K. Kämäräinen
Department of Signal Processing, Tampere University of Technology
Jussi Halme, Jyrki Latokartano
Department of Mechanical engineering and industrial systems, Tampere University of Technology
Anders Glent Buch
Maersk McKinney Moller Institute, University of Southern Denmark

- Curvature filtering and region pruning methods to improve 3D correspondence based object pose estimation.
- The methods are evaluated using three different state-of-the-art correspondence selection methods.
- Experiments show that the methods consistently robustify the initial versions of the algorithms.

Multi-sensor Payload Detection and Acquisition for Truck-Trailer AGVs

Sebastian Buck, Richard Hanten and Andreas Zell
Cognitive Systems, University of Tübingen, Germany
Karsten Bohlmann
EK Automation, Germany

- Real-time detection of payload carts for freely navigating automated guided vehicles.
- Containers are detected with 2D laser scanners.
- The pose is verified and refined using a time-of-flight camera.
- A reactive control law is proposed for payload acquisition.

Driving in the Matrix: Can Virtual Worlds Replace Human-Generated Annotations for Real World Tasks?

Matthew Johnson-Roberson, Charles Barto, Rounak Mehta, Sharath Nittur Sridhar, Karl Rossaen, and Ram Vasudevan
College of Engineering, University of Michigan, USA

- We use purely simulated images to detect cars in real imagery.
- We demonstrate the power of training on 200,000 images for improved results over current public data.
- We show the challenges of domain adaptation across real data.
- We publicly released the code to capture from a modern video game engine and the full dataset containing bounding boxes and pixel annotations.
Machine Learning and Coresets for Automated Real-Time Video Segmentation of Laparoscopic and Robot-Assisted Surgery

Mikhail Volkov, Daniel A. Hashimoto, Guy Rosman, Ozanar R. Meireles, Daniela Rus
1) CSAIL, MIT, USA, 2) Department of Surgery, MGH, USA

- K-segment coresets enable real-time analysis of surgical video.
- A spatial BOW model for surgery phase classification w/ small training sets.
- Coresets enable stream segmentation w/ linear segment classifiers.
- Results on laparoscopic surgery videos, w/ 92% accuracy.

Accurate Angular Velocity Estimation with an Event Camera

Guillermo Gallego and Davide Scaramuzza
Robotics and Perception Group, University of Zurich, Switzerland

- Estimate rotational motion using events.
- No need of optical flow estimation or image intensity reconstruction.
- Idea: Maximize contrast of accumulated event polarities along motion lines.
- Estimate high-speed motions: ~1000 º/s.
- Comparable accuracy to Motion-Capture System or IMU.
Multi-Objective Search for Optimal Multi-Robot Planning with Finite LTL Specifications and Resource Constraints

Philipp Schillinger1,2 and Mathias Bürger1
1 Bosch Center for Artificial Intelligence, Germany
2 KTH Royal Institute of Technology, Sweden

- Linear Temporal Logic (LTL) allows to formulate complex goals for autonomous systems
- Generating execution strategies for a team requires planning coupled with task allocation
- We model the LTL multi-robot planning problem as a multi-objective search
- Discrete LTL specifications can be combined with continuous resource constraints

A Layered HMM for Predicting Motion of a Leader in Multi-Robot Settings

Sina Solaimanpour and Prashant Doshi
THINC Lab, Department of Computer Science, University of Georgia, Athens, GA 30602, USA

- Vehicles being e-towed and telepresence robots following others suffer from persistent occlusion while following
- Nested particle filter (NPF) allows both self-localization and tracking of another robot simultaneously using a motion model
- Monte Carlo layered HMM (MCLHMM) is a novel model that allows online prediction of other’s motion with good accuracy
- Observations are used for parameter learning

Algorithm for Optimal Chance Constrained Linear Assignment

Fan Yang and Nilanjan Chakraborty
Department of Mechanical Engineering, Stony Brook University, USA

- Chance Constrained Linear Assignment Problem (CC-LAP): Given n robots and n tasks, with uncertain payoff for robot-task pairs find an assignment with maximum total payoff (say y) such that, irrespective of the actual values the random payoffs, the probability of the actual payoff being less than y is greater than a pre-specified probability (say 0.99).
- Solution: Novel iterative approach that uses the solution of a small number of Risk Averse Linear Assignment Problems (RA-LAP) with deterministic payoffs to solve the stochastic CC-LAP.
- RA-LAP is same as classical LAP where the robot-task payoff is a weighted combination of the mean and variance (weight is called risk-aversion index).
An Adaptable, Probabilistic, NBV Algorithm for Reconstruction of Unknown 3D Objects

Jonathan Daudelin and Mark Campbell
Mechanical Engineering, Cornell University, USA

• Next Best View Planner for reconstructing unknown objects
• Probabilistic framework for predicting information gain from candidate viewpoints
• Dynamically adapts to any object size
• Computationally efficient

A Hybrid Method for Online Trajectory Planning of Mobile Robots in Cluttered Environments

Leobardo Campos-Macias, David Gómez-Gutiérrez, Rodrigo Aldana-López, Rafael de la Guardia and José I. Parra-Vilchis
Multi-Agent Autonomous Systems Lab, Intel Labs

• Our approach is a fusion of sampling-based techniques and model-based optimization via quadratic programming.
• The main contribution of this work is the formulation of a convex optimization problem over the generated obstacle-free path that is guaranteed to be feasible.
• The algorithm was applied to the fluid navigation of a quadcopter in one of the most densely clutter scenario reported to date.

Composite image of a quadcopter in one of the experiments.
**Multi-Robot Systems 2**

**Chair Mikko Lauri, University of Hamburg**
**Co-Chair Anna Valente, SUPSI-ISTePS**

### Session TUB5 Rm. 4511/4512

**Tuesday, May 30, 2017, 11:30–12:45**

#### 11:30–11:35 TUB5.1

**Tunneling-based Self-reconfiguration of Heterogeneous Sliding Cube-shaped Modular Robots in Environments with Obstacles**

Hiroshi Kawano

NTT Communication Science Laboratories, NTT Corporation, Japan

- The proposed method does not assume convex motion of sliding cubic-module.
- The proposed method combines homogeneous tunneling-based transformation and heterogeneous permutation in goal configuration.
- The proposed method can be applied to arbitrary robot structures with $2 \times 2 \times 2$ cubic meta-modules.
- Proof of the quadratic operation time cost of the reconfiguration process is provided.
- Only the space occupied by start and goal configurations is needed in the reconfiguration process; therefore, the method is applicable to the environments with obstacles.

#### 11:40–11:45 TUB5.2

**Distributed Fixed-Time Cooperative Tracking Control for Multi-Robot Systems**

Boda Ning, Jiong Jin, Jinchuan Zheng, Qing-Long Han

School of Software and Electrical Engineering, Swinburne University of Technology, Australia

- Achieving the cooperative tracking for multi-robot systems in a fixed time;
- A new class of observers is proposed, under which the leader state is estimated by the followers in a fixed time;
- An observer-based fixed-time controller is proposed such that the estimated leader state is tracked in a fixed time;
- The results are extended to multi-robot systems with non-holonomic dynamics.

#### 11:45–11:50 TUB5.3

**Multi-Robot Active Information Gathering with Periodic Communication**

Mikko Lauri and Simone Frinotrop

Department of Informatics, University of Hamburg, Germany

- Team of robots executing information gathering task with periodic communication capability
- Introduce extension of decentralized POMDPs to information gathering rewards
- Feasibility demonstrated in target tracking problem

#### 11:50–11:55 TUB5.4

**Bipartite Graph Matching-based Coordination Mechanism for Multi-robot Path Planning under Communication Constraints**

Ayan Dutta and Prithviraj Dasgupta

Department of Computer Science, University of Nebraska at Omaha, USA

- We propose a bipartite graph matching-based distributed coordination mechanism for multiple robots to avoid collisions and reach goals by travelling shorter paths.
- Robots have limited communication range and they only coordinate with other robots when they are in close proximity.
- Our algorithm is proved to be correct, convergent and helps robots to travel lesser path (up to 4.2 times) than a comparable heuristic.
Scalable Accelerated Decentralized Multi-Robot Policy Search in Continuous Observation Spaces

Shayegan Omidshafiei\textsuperscript{1}, Christopher Amato\textsuperscript{2}, Miao Liu\textsuperscript{3}
Michael Everett\textsuperscript{1}, Jonathan P. How\textsuperscript{1}, and John Vian\textsuperscript{4}
\textsuperscript{1}LIDS, MIT, MA, \textsuperscript{2}CCIS, Northeastern University, MA, USA
\textsuperscript{3}IBM, NY, USA, \textsuperscript{4}Boeing Research & Technology, WA, USA

- We present kernel-based stochastic policy representation for scalable continuous observation space decision-making
- Algorithm outperforms existing discrete search approaches for complex decentralized and partially-observable planning domain


Shayegan Omidshafiei\textsuperscript{1}, Shih-Yuan Liu\textsuperscript{1}, Michael Everett\textsuperscript{1}, Brett T. Lopez\textsuperscript{1}, Christopher Amato\textsuperscript{2}, Miao Liu\textsuperscript{3}
Jonathan P. How\textsuperscript{1}, and John Vian\textsuperscript{4}
\textsuperscript{1}LIDS, MIT, MA, USA, \textsuperscript{2}CCIS, Northeastern University, MA, USA
\textsuperscript{3}IBM, NY, USA, \textsuperscript{4}Boeing Research & Technology, WA, USA

- Hierarchical Bayesian approach to model noise statistics of low-level classifier outputs
- Enables multi-agent planners to perform policy search with perception-in-the-loop
- Real-time hardware experiments, observation pipeline fully onboard team of 4 quadrotors
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<th>Time</th>
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<td>11:30–11:35</td>
<td>TUB6.1</td>
<td>Preference Learning on the Execution of Collaborative Human-Robot Tasks</td>
<td>Thibaut Munzer, Marc Toussaint, Flowers, Inria, France, MLR, USTT, Germany, Manuel Lopes, INESC-ID, IST, Portugal</td>
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<td>11:40–11:45</td>
<td>TUB6.3</td>
<td>Self-supervised learning of tool affordances from 3D tool representation through parallel SOM mapping</td>
<td>Tanis Mar, Vadim Tikhanoff, Giorgio Metta and Lorenzo Natale, iCub Facility, Italian Institute of Technology, Italy</td>
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<td>11:50–11:55</td>
<td>TUB6.5</td>
<td>Learning to Gather Information via Imitation</td>
<td>Sanjiban Choudhury, Robotics Institute, Carnegie Mellon University, USA, Ashish Kapoor, Gireeja Ranade and Debadeepta Dey, Microsoft Research, USA</td>
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<td>11:35–11:40</td>
<td>TUB6.2</td>
<td>Learning composable models of parameterized skills</td>
<td>Leslie Kaelbling and Tomaso Lozano-Perez, CSAIL, MIT, USA</td>
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<td>11:45–11:50</td>
<td>TUB6.4</td>
<td>Constrained Bayesian Optimization of Combined Interaction Force/Task Space Controllers for Manipulations</td>
<td>Danny Drieß, Peter Englert and Marc Toussaint, Machine Learning &amp; Robotics Lab, University of Stuttgart, Germany</td>
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<td>11:55–12:00</td>
<td>TUB6.6</td>
<td>Design and optimal control of an under-actuated cable-driven micro-macro robot</td>
<td>Luca Barbazza and Giulio Rosati, Department of Management and Engineering, University of Padua, Italy, Damiano Zanotto, INESC-ID, IST, Portugal, Sunil K. Agrawal, Department of Mechanical Engineering, Columbia University, USA</td>
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**Session TUB6** Rm. 4611/4612  Tuesday, May 30, 2017, 11:30–12:45

**Learning and Adaptive Systems 2**

Chair Lynne Parker, University of Tennessee

Co-Chair Matthew Howard, King’s College London
A Sample-Efficient Black-Box Optimizer to Train Policies for Human-in-the-Loop Systems with User Preferences

Nitish Thatte¹, Helei Duan², and Hartmut Geyer¹
¹Robotics institute, ²Mechanical Engineering, Carnegie Mellon University, USA

- Optimizing human-in-the-loop systems can be difficult as it can be hard to define the objective
- We may be able to learn from preferences to optimize systems via user feedback
- We present a Bayesian optimization method that uses preferences between pairs of parameters
- The algorithm chooses queries that it expects will decrease uncertainty in the distribution of optima

Apprenticeship Learning in an Incompatible Feature Space

Gakuto Masuyama¹ and Kazunori Umeda¹
¹Department of Precision Mechanics, Faculty of Science and Engineering, Chuo University, Japan

- Apprenticeship learning in which an expert and agent are assumed to observe different features.
- Feature expectation in the agent feature space is estimated in closed-form by using conditional density estimation technique.
- Simulation results demonstrated the proposed method successfully transferred a reward function among heterogeneous MDP.
Development of an Optical Fiber-based Sensor for Grasping and Axial Force Sensing

Pouya Soltani Zarrin, Abelardo Escoto, Ran Xu, Rajni V. Patel, Michael D. Naish and Ana Luisa Trejos

Canadian Surgical Technologies and Advanced Robotics, Lawson Health Research Institute and Western University, London, Ontario, Canada

- A sterilizable sensorized needle-driver style grasping instrument has been designed and developed.
- Accuracies of 0.19 N and 0.26 N were achieved for the grasping and axial sensing, respectively.
- Fiber Bragg Grating sensors were chosen due to their sterilizability and high sensitivity.

Shape-independent Hardness Estimation Using Deep Learning and a GelSight Tactile Sensor

Wenzhen Yuan1, Chenzhuo Zhu2, Andrew Owens1,3, Mandayam Srinivasan1,4, Edward Adelson1

1MIT, US 2Tsinghua University, China 3UC Berkeley, US 4UCL, UK

- Proposed a method of measuring hardness with tactile sensor in loosely-controlled contact condition
- Sensor being used: a high-resolution tactile sensor, GelSight, to measure object shape and force
- Applied convolutional neural network (CNN) for data analysis
- Build a dataset of 7,000 contacts on objects with varied shapes and hardness

Low-cost 3-axis soft tactile sensors for the human-friendly robot Vizzy

T. Paulino1, P. Ribeiro1,2, M. Neto2, S. Cardoso1,2, A. Schmidt2, J. Santos-Victor2, A. Bernardino4 and L. Jamone3

1ID, Physics, IST, Portugal, 2INESC-MN, Portugal, 3Waseda University, Japan, 4ISR, IST, Portugal, 5ARQ, Queen Mary University of London, UK.

- Low-cost and easy to fabricate 3D soft tactile sensor, based on magnetic technology.
- All components are cheap and easy to retrieve and to assemble.
- High sensitivity, low hysteresis, good repeatability and mechanical robustness.
- Sensors were integrated on a robot hand, and been able to measure normal forces <10 mN and shear forces <20 mN.

Sensorless Kinesthetic Teaching of Robotic Manipulators Assisted by Force Control

M. M. G. Ardiakani, R. Johansson and A. Robertsson

Automatic Control, LTH, Lund University, Sweden

- Lead-through programming (LTP): the user manually guides the manipulator to teach trajectories.
- This paper presents a sensorless approach to LTP for redundant robots.
- The active implementation (LTP assisted by Force Control) utilizes an admittance control.
- The external forces applied by the user are estimated with a Kalman filter. The static friction is mitigated by a dithering technique.

Accurate contact localization and indentation depth prediction with an optics-based tactile sensor

P. Piacenza1, W. Dang2, E. Hannigan2, J. Espinal1, I. Hussein1, I. Kymissis2 and M. Ciocarlie1

Dept. of Mechanical Eng., Electrical Eng., Columbia University, USA

- A tactile sensor based on light transport through an optically clear elastomer.
- We leverage two different modes of light transport to improve our sensor sensitivity to light and hard indentations.
- We use data driven techniques to directly learn the mapping between our signals and the contact location and depth.

Bio-inspired ciliary force sensor for robotic platforms

P. Ribeiro1,2, M. A. Khan4, A. Alfadhel1, J. Kosel5, F. Franco1,2, S. Cardoso1,2, A. Bernardino4, A. Schmidt2, J. Santos-Victor2 and L. Jamone3

1INESC-MN, Portugal, 2ID, Physics, IST, Portugal, 3CEMSE, KAUST, Saudi Arabia, 4ISR, IST, Portugal, 5ARQ, Queen Mary University of London, UK

- We present a miniaturized force sensor inspired by biological cilia, designed to detect very small forces using magnetic technology.
- Experiments show that a minimum force of 333 µN can be detected.
- Accurate simulations were performed to optimize the structure of the fabricated sensor, using a novel simulation model that was successfully validated against the experimental results.
Exploiting sensor symmetry for generalized tactile perception in biomimetic touch

Benjamin Ward-Cherrier, Luke Cramphorn and Nathan Lepora
Bristol Robotics Laboratory and Department of Engineering Mathematics, University of Bristol, UK

- Standard classification methods in robot touch require extensive training, limiting their practicality.
- We consider angle and position classification with a tactile fingertip (the BRL TacTip).
- Geometric transformations were applied to tactile data based on the TacTip's intrinsic symmetry, reducing training time 12-fold with comparable localization performance.
- Methods were applied to a contour following task, demonstrating greatly reduced training for robust performance.

Exploratory tactile servoing with active touch

Nathan F. Lepora, Kirsty Aquilina & Luke Cramphorn
Bristol Robotics Laboratory & Department of Engineering Mathematics, University of Bristol, U.K.

- Key problem in tactile robotics is to combine tactile perception & control for robust and intelligent robot behavior.
- Investigated with contour following using a 3d-printed tactile fingertip (the BRL TacTip) on a robot arm.
- We use a single control loop for active perception and tactile exploration.
- Method simplifies with tactile servoing to maintain sensor orientation on object.
- Robust & accurate performance on laminar objects, e.g. disks and spirals.
Using Intentional Contact to Achieve Tasks in Tight Environments
J. Rogelio Guadarrama-Olvera, Emmanuel Dean-Leon and Gordon Cheng
Institute for Cognitive Systems, Technical University of Munich, Germany
www.ics.ei.tum.de
• Intentional Contact defined to modify the environment to achieve tasks.
• Contact regulated with tactile feedback.
• Collision avoidance with directly measured potential fields.
• Hierarchy rearrangement to escape from classic potential fields local minimum.

Experimental results
Development of a Block Machine for Volleyball Attack Training

Kosuke Sato\textsuperscript{1}, Keita Watanabe\textsuperscript{2}, Shuichi Mizuno\textsuperscript{2}
Masayoshi Manabe\textsuperscript{1}, Hiroaki Yano\textsuperscript{1} and Hiroo Iwata\textsuperscript{1}

\textsuperscript{1}University of Tsukuba, Japan
\textsuperscript{2}Japan Volleyball Association, Japan

• A system that consists of three robots to imitate the motion of top volleyball blockers.
• It can be continuously used in an actual practice field to improve attack practice.
• An application with a graphical user interface to enable a coach to manipulate these robots
• It enables the coach to control block motions and change the parameters

Hierarchical Cascade Controller for Assistance Modulation in a Soft Wearable Arm Exoskeleton

Binh Khanh Dinh\textsuperscript{1}, Michele Xiloyannis\textsuperscript{1}, Chris Wilson Antuwan\textsuperscript{1}, Leonardo Cappello\textsuperscript{2}, and Lorenzo Masia\textsuperscript{1}

\textsuperscript{1}Mechanical Engineering, Nanyang Technological University, Singapore
\textsuperscript{2}School of Engineering and Applied Science, Harvard University, USA

• A novel soft wearable exoskeleton (exosuit) using Bowden-cable transmission for human arm assistance.
• Hierarchical Cascade Controller considering all the aspects ranging from human motion intention detection to adaptive compensation for nonlinear effects (i.e. backlash and friction).
• Assistance modulation by ‘assisted-as-needed’ admittance controller meaning the level of assistance depends on the voluntary motion capacity of the subjects.

Figure: The soft arm exosuit with the Bowden-cable transmission worn by the user.
**Multilegged Robots**

Chair Claudio Semini, Istituto Italiano di Tecnologia  
Co-Chair Navinda Kottege, CSIRO

### 11:30–11:35 TUB9.1

**The Multilegged Autonomous eXplorer (MAX)**
A. Elfes, R. Steindl, F. Talbot, F. Kendoul, P. Sikka, T. Lowe, N. Kottege, M. Bjelonic, R. Dungavell, T. Bandyopadhyay, M. Hoerger, B. Tam and D. Ryzt  
CSIRO Robotics and Autonomous Systems Lab

- MAX is an ultralight, six-legged robot with 18 DOFs.
- MAX is 2.25 m tall at full height and weighs 59.8 kg. In a cruise stance the body is 1.5 m above the ground.
- MAX is used for research in modelling, planning, control and autonomous navigation of Ultralight Legged Robots subject to flexing, oscillations and swaying.

### 11:40–11:45 TUB9.3

**A Testbed that Evolves Hexapod Controllers in Hardware**
Huub Heijnen, David Howard, and Navinda Kottege  
Autonomous Systems Lab, CSIRO, Australia

- Testbed allows 24/7 optimisation
- Stage 1: Multi-Objective Evolutionary Algorithm bootstraps a population of controllers (PI and foot-tip arcs for 3 leg-pairs) to minimise energy, and maximise stability and smoothness
- Stage 2: Hill-climber specialises a selected controller further based on desired ordering of objectives, per leg.
- Controllers are sensitive to hardware state & mission type.

### 11:50–11:55 TUB9.5

**Quasi-Static and Dynamic Mismatch for Door Opening and Stair Climbing With a Legged Robot**
T. Turner Topping†, Gavin Kenneally‡ and Daniel E. Koditschek†  
†ESE, University of Pennsylvania, USA  
‡MEAM, University of Pennsylvania, USA

- We quantify the notion of robotic fitness by developing necessary conditions for quasi-static solutions to human-scale tasks
- We present empirical dynamic workarounds for door opening and stair climbing
- We are able to accomplish human-scale tasks that are otherwise unachievable with a 0.4 meter quadruped using dynamical maneuvers

### 11:35–11:40 TUB9.2

**Empirical Validation of a Spined Sagittal-Plane Quadrupedal Model**
Jeffrey Duperret and Daniel Koditschek  
Electrical and Systems Engineering, University of Pennsylvania, U.S.A.

- We present a model for robotic spined sagittal-plane quadrupedal locomotion.
- This model is demonstrated on a power-autonomous bounding spined quadrupedal robot.
- The model is sufficiently accurate as to roughly describe the robot’s mass center trajectory.

### 11:45–11:50 TUB9.4

**Between-Leg Coupling Schemes for Passively-Adaptive Non-Redundant Legged Robots**
Oren Y. Kanner and Aaron M. Dollar  
Dept. of Mechanical Engineering and Materials Science, Yale University, USA  
Nicolas Rojas  
Dyson School of Design Engineering, Imperial College London, UK

- Legged robots can adapt to terrain with redundant actuation, but this can lead to overconstraint.
- Non-redundant legged robots can achieve full control and adaptability while reducing complexity and cost.
- A strategy for designing between-leg couplings for adaptive swing and robust stance behavior is presented.
- A 4-RR case study is analyzed through stance simulations with experimental validation.

### 11:55–12:00 TUB9.6

**Probabilistic Contact Estimation and Impact Detection for State Estimation of Quadruped Robots**
Marco Camurri†, Maurice Fallon†, Stéphane Bazeille‡, Andreea Radulescu,† Victor Barasu,† Darwin G. Caldwell, and Claudio Semini†  
†Advanced Robotics, Istituto Italiano di Tecnologia, Italy  
‡School of Informatics, University of Edinburgh, UK

- Leg Odometry without contact sensors, fused with inertial process model in a modular EKF
- Contact classification with logistic regression on GRF computed from joint torques
- Online covariance with impact detection by GRF analysis and inter-leg velocity variance
- Tested on different gaits and more than one hour of experiments with the 85 kg dynamic legged robot HyQ
Trajectory and Foothold Optimization using Low-Dimensional Models for Rough Terrain Locomotion

C. Mastalli\textsuperscript{1}, M. Focchi\textsuperscript{1}, I. Havoutis\textsuperscript{2,4}, A. Radulescu\textsuperscript{1}, S. Calinon\textsuperscript{2}, J. Buchli\textsuperscript{3}, D. G. Caldwell\textsuperscript{1}, C. Semini\textsuperscript{1}

\textsuperscript{1}Department of Advanced Robotics, Istituto Italiano di Tecnologia, Italy
\textsuperscript{2}Robot Learning and Interaction, Idiap Research Institute, Switzerland
\textsuperscript{3}Agile and Dexterous Robotics Lab, ETH Zurich, Zurich, Switzerland
\textsuperscript{4}Oxford Robotics Institute, Department of Engineering Science, University of Oxford, UK

- Jointly optimize CoM motions, step durations and foothold locations, while considering terrain topology
- Gait adapts to the terrain by modulating the trunk attitude and ensuring dynamic stability
- Receding horizon planning for synthesizing walking gaits
- Robust and accurate locomotion over challenging terrain

HyQ crossing stepping stones with various heights

Trajectory Optimization Through Contacts and Automatic Gait Discovery for Quadrupeds

Michael Neunert, Farbod Farshidian, Alexander W. Winkler, Jonas Buchli
Agile & Dexterous Robotics Lab, ETH Zurich, Switzerland

- Whole-body Trajectory Optimization through contacts
- Automatic discovery of gaits
- Contact timings are an outcome of the optimization and not pre-specified
- Successful hardware experiments on the quadrupedal robot HyQ
Biologically-inspired auditory perception during robotic bone milling

Yu Dai¹, Yuan Xue², Jianxun Zhang¹, and Jianmin Li³
¹Department of Orthopedic Surgery, Tianjin Medical University, China
²Key Lab for Mechanism Theory and Equipment Design, Tianjin University, China

- Microphone is mounted on robot arm and measures sound generated from bone milling.
- Mechanism of human auditory sense and proposed auditory perception method

Deployable stabilization mechanisms for endoscopic procedures

T. Ranzani, S. Russo, F. Schwab, C.J. Walsh, R.J. Wood

- Endoscope’s flexibility (necessary for navigating through the GI tract) limits distal manipulation and stability during surgical procedures.
- We propose a deployable endoscopic add-on aimed at locally counteracting forces applied at the tip of an endoscope.
- We focus on the fabrication and experimental characterization of three different structures and present some preliminary designs and integration strategies to mount them on top of current flexible endoscopes.

Preliminary Results on Energy Efficient 3D Prosthetic Walking with a Powered Compliant Transfemoral Prosthesis

Huihua Zhao
SRI Robotics, Menlo Park, CA, USA

- A transfemoral prosthetic, AMPRO3, is designed and used to achieve 3D efficient walking
- A Hybrid, 8 Domain, human-and-prosthetic model and optimization generates walking gait
- Treadmill testing in lab shows the realized multi-contact walking is successful and efficient

A rolling-diaphragm transmission for remote MR-guided needle insertion

Natalie Burkhard, Samuel Frishman, Alexander Gruebele, Roger E. Goldman, Bruce Daniel, Mark Cutkosky
Mechanical Engineering, Stanford University, United States

- Passive, force transparent needle manipulator for improved MR-guided interventions
- Position tracking and force transparency characterized and demonstrated to be clinically relevant
- Experiments in phantom tissue indicate a 77% success rate in detecting membrane punctures of ~0.5N
First Demonstration of Simultaneous Localization and Propulsion of a Magnetic Capsule in a Lumen using a Single Rotating Magnet
Katie Popek and Tucker Hermans
School of Computing, University of Utah, USA
Jake Abbott
Department of Mechanical Engineering, University of Utah, USA

- Prior work in active capsule endoscopy using rotating magnetic fields required decoupled localization and propulsion.
- We experimentally demonstrate simultaneous localization and capsule propulsion through multiple trajectories using a single external rotating magnet.
- This system results in 3x speed up compared to the previous decoupled approach.

Efficient Proximity Queries for Continuum Robots on Parallel Computing Hardware
Konrad Leibrandt and Guang-Zhong Yang
Hamlyn Centre for Robotic Surgery
Imperial College London, United Kingdom

- Proximity calculation for continuum robots using an algebraic approach
- Automatic generation of geometrical primitives based on the robot shape
- Implementation considerations for accelerators such as GPUs
- Benchmark results for GPUs and CPUs:
  - polynomial root-finding
  - proximity calculation
A Virtual Paper Model of a Three Piece Brassiere Cup to Improve the Efficiency of Cup Design Process

Hidefumi Wakamatsu, Eiji Morinaga, and Eiji Arai
Dept. of Manufacturing Science, Osaka Univ., Japan
Takahiro Kubo
Wacoal Holdings Corp., Japan

• The brassiere cup shape is determined by creating a paper model and refining it.
• Predicting the shape of the paper model with a simulation would improve design efficiency.
• The shape of the paper model is represented as combination of developable surfaces.
• Minimizing the potential energy of surfaces derives a stable shape of the paper model.

An Improved Tool Path Algorithm for Fused Filament Fabrication

Samuel Lensgraf and Ramgopal Mettu
Department of Computer Science
Tulane University

• We present a local search algorithm for tool path planning that leverages part geometry to minimize the wasted motion during printing.
• On a benchmark of 400+ models we achieve 62% mean reduction in wasted motion over traditional slicing.
• We also give evidence that our local search method is close to optimal in some cases, using calculate an instance specific lower bound for 30 models using a novel Integer Linear Programming formulation.

Computational Abstractions for Interactive Design of Robotic Devices

Ruta Desai, Ye Yuan and Stelian Coros
Robotics Institute, Carnegie Mellon University, USA

• Our goal is to make robotics more accessible.
• Towards this end, we present a general design abstraction and a visual design system for on-demand generation of customized robots using modular electromechanical components.
• Our system allows users to efficiently create robots through design space exploration and simulation-based feedback.
• In particular, a manual mode that supports forward design, and an auto-completion method are provided for user design.

RoboFDM: A Robotic System for Support-Free Fabrication using FDM

Chenming Wu1, Chengkai Dai2, Guoxin Fang2
Yong-Jin Liu1 and Charlie C.L. Wang2
1 Department of Computer Science and Technology, Tsinghua University, China
2 Department of Design Engineering and TU Delft Robotics Institute, Delft University of Technology, Netherlands

• Target: print 3D models without support-structures using FDM.
• Use a robotic arm providing 6-DOF motion to the platform of material accumulation.
• A new algorithm is developed to decompose models into support-free parts that can be printed one by one in a collision-free sequence.
• Our results show that the proposed system works well on a variety of 3D models.

Interactive, Iterative Robot Design

Bradley Canaday, Samuel Zapolsky and Evan Drumwright
Computer Science Dept., George Washington University

• Simulation-aided performance analysis of controlled robotic systems
• Iterative morphological update process toward improving robot performance
• Initial, brittle robot design (top) walks and then breaks
• Updated robot design (bottom) demonstrates durable performance and walks twice as fast

Adaptive Task Scheduling for an Assembly Task Co-worker Robot Based on Incremental Learning of Human’s Motion Patterns

Jun Kinugawa, Akira Kanazawa
Shogo Arai and Kazuhiro Kosuge
Department of Robotics, Tohoku University, Japan

• We propose an adaptive task scheduling system for co-worker robot in an automobile assembly line
• Proposed system learns the working position and worker’s motion trajectory using online algorithm
• Using the prediction results, the robot’s delivery tasks are determined adaptively
• Experimental results show that the proposed system improves work efficiency by decreasing worker’s waiting time
PaintPots: Low Cost, Accurate, Highly Customizable Potentiometers for Position Sensing

Tarik Tosun, Daniel Edgar, Chao Liu, Thulani Tsabedze, and Mark Yim
Dept. of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, USA

- Method to make customizable potentiometers with conductive spray paint
- Many shapes and sizes possible, including curved surfaces
- Easy to make with common tools
- Cost about $1 USD each
- Performance comparable to commercial pots
- Create 2D sensors that capture handwriting (touchpad)

Uncertainty in Monotone Co-Design Problems

Andrea Censi
ETH Zürich

- Context: a compositional theory of co-design, for robotics and beyond.
- This paper deals with the introduction of uncertainty in the co-design framework.
- Software and online demo are available at https://co-design.science
Enhancing Joint Torque Control of Series Elastic Actuators with Physical Damping
Min Jun Kim, Alexander Werner, Florian Loeffl, Christian Ott
Robotics and Mechatronics Center, DLR, Germany

- SEA torque control usually requires D-control
  - Desired torque is a function of velocity in most of applications
  - D-control implies acceleration feedback
- Physical damping converts P-control into D-action
  - No acceleration feedback
  - Enhances torque control capability

Efficiently Tunable Positive-Negative Stiffness Actuator
Abhinav Dahiya and David J. Braun
Dynamics and Control Laboratory
Singapore University of Technology and Design

- Compliant actuation concept allowing control over equilibrium position and joint stiffness using a single motor unit.
- The actuator combines a passive positive feedback mechanism with an efficiently tunable negative feedback mechanism.
- The actuator may enable the design of an efficiently tunable compliant prosthetic leg.

Analytical Conditions for the Design of Variable Stiffness Mechanisms
Tze Hao Chong, Vincent Chalvet and David J. Braun
Dynamics and Control Laboratory
Singapore University of Technology and Design

- Analytical approach to the design of variable stiffness mechanisms.
- Classes of mechanisms were identified using a general potential energy model and user-defined design conditions.
- Identification of mechanisms which enable infinite range stiffness modulation using bounded input motor forces.

A Geometrically-Amplified In-Plane Piezoelectric Actuator for Mesoscale Robotic Systems
Peter A. York and Robert J. Wood
Harvard University, USA

- Achieves 20x displacement amplification.
- Performance metrics include: blocked force (20 mN), displacement (115 um), bandwidth (3 kHz), and power density (172 W/kg).
- Printed circuit MEMS fabrication process is described in detail.
- Can be used in servo or power delivery applications.
Modeling and Inverse Compensation of Hysteresis in Supercoiled Polymer Artificial Muscles

Jun Zhang, Kaushik Iyer, Anthony Simeonov, and Michael C. Yip
University of California San Diego, La Jolla, CA 92093 USA

- Supercoiled polymer actuators exhibit significant strain and fast speed
- Existing studies unable to model the hysteresis and produce over 15% error
- Proposed models for contraction length – voltage hysteresis under different loads
- Realized open-loop position control through hysteresis inverse compensation

On the Sensor Design of Torque Controlled Actuators: A Comparison Study of Strain Gauge and Encoder Based Principles

Navvab Kashiri, Jorn Malzahn, and Nikos G. Tsagarakis
Department of Advanced Robotics, Istituto Italiano di Tecnologia, Italy

This work proposes and evaluates two joint torque sensing elements based on strain-gauge and deflection-encoder principles.

The two designs are elaborated and evaluated from different perspectives:
- resolution
- non-axial moments load crosstalk
- torque ripple rejection
- stiffness and bandwidth
- noise/residual offset level
- thermal/time dependent signal drift
Planning

Chair Gim Song Soh, Singapore University of Technology and Design
Co-Chair Kei Okada, The University of Tokyo

14:45–14:50 TUC2.1
Planning Method for a Wrapping-with-Fabric task Using Regrasping
Naohiro Hayashi, Takashi Suehiro and Shunsuke Kudoh
The University of Electro-Communications, Japan

• Inter- and intra-hand passing is required for wrapping a long fabric to an object
• The inter- and intra-hand passing is planned from a motion-transition graph of a robot
• The motion-transition graph represents the reliability of wrapping movements

A General Formal Framework for Multi-Agent Meeting Problems
Yusuf Izmirliloglu, Bahadir A. Pehlivan, Misra Turp, Esra Erdem
Faculty of Engineering and Natural Sciences, Sabanci University, Turkey

• The multi-agent meeting (MAM) problem asks for a meeting location for multiple heterogeneous agents such that the agents can get together within a given time or budget, possibly using different modes of transportation, subject to some constraints and preferences to visit specific locations on their ways to the meeting location.
• Examples: autonomous driverless cars deciding for a common place so that their passengers can meet; robots at a factory floor deciding for a location to exchange the materials they carry.
• We mathematically model MAM as a graph problem, prove its intractability, and introduce a novel formal method to solve it and its variations using AI methods.

Towards Robotic MAGMaS: Multiple Aerial-Ground Manipulator Systems
1Nicolas Staub, 2Mostafa Mohammadi, 1Davide Bicego,
2Domenico Prattichizzo, and 1Antonio Franchi
1LAAS-CNRS, Université de Toulouse, CNRS, France
2Dept. of Information Engineering and Mathematics, University of Siena, Italy

• Cooperative manipulation for heterogeneous multi-robot system with aerial and ground manipulators
• Optimization based control allocation to respect all system constraints and maximize force manipulability index
• Disturbance and imperfection robustness
• Experiment of cooperative manipulation of long flexible object

Plan Explicability and Predictability for Robot Task Planning
Yu Zhang, Sarath Sreedharan, Anagha Kulkarni, Tathagata Chakraborti and Subbarao Kambhampati
Computer Science and Engineering, Arizona State University, USA
Hankui Zhuo, Computer Science, Sun Yat-sen University, China

• Introduce plan explicability and predictability for intelligent robots to synthesize plans that are more comprehensible to humans
• Interpret human understanding of a plan as a labeling process, learn the labeling scheme of humans for agent plans from training examples using conditional random fields.
• Use the learned model to label a new plan to compute its explicability and predictability to inform planning
• Provide evaluations on a synthetic domain and with a physical robot

Optimal Path Planning and Coverage Control for Multi-Robot Persistent Coverage in Environments with Obstacles
José M. Pallacios-Gasós, Eduardo Montijano and Carlos Sagüés
I3A, University of Zaragoza, Spain
Zeynab Talebpour and Alcherio Martinoli
DISAL, EPFL, Switzerland

• Aim: maintain a desired coverage level (temperature, dust) that deteriorates over time in an environment.
• Each robot locally finds using FMM optimal coverage paths that also avoid obstacles.
• A coverage action controller allows each robot to produce the optimal coverage at each point.
• Simulations and real experiments validate the whole approach.

14:50–14:55 TUC2.2
Online Estimation of Object–Environment Constraints for Planning of Humanoid Motion on a Movable Object
Shunichi Nozawa and Shinataro Noda and Masaki Murooka
Creative Informatics Department, UTokyo, Japan

• Deal with Motion On a Movable Object (MOMO) for a humanoid robot
• Propose representation of robot-and-object balance constraints which can be used in multi-contact motion planner and controller
• Propose estimation of object-environment constraints based on robot’s sensor information
• Achieve carrying-and-climbing of a stepladder with unknown mass properties on a real robot

15:00–15:05 TUC2.3
A General Formal Framework for Multi-Agent Meeting Problems
Bahadir A. Pehlivan, Misra Turp, Esra Erdem
Faculty of Engineering and Natural Sciences, Sabanci University, Turkey

15:05–15:10 TUC2.4
Towards Robotic MAGMaS: Multiple Aerial-Ground Manipulator Systems
Nicolas Staub, Mostafa Mohammadi, Davide Bicego,
Domenico Prattichizzo, and Antonio Franchi

15:10–15:15 TUC2.5
Plan Explicability and Predictability for Robot Task Planning
Yu Zhang, Sarath Sreedharan, Anagha Kulkarni, Tathagata Chakraborti and Subbarao Kambhampati
Computer Science and Engineering, Arizona State University, USA
Hankui Zhuo, Computer Science, Sun Yat-sen University, China

15:15–16:00 TUC2.6
Optimal Path Planning and Coverage Control for Multi-Robot Persistent Coverage in Environments with Obstacles
José M. Pallacios-Gasós, Eduardo Montijano and Carlos Sagüés
I3A, University of Zaragoza, Spain
Zeynab Talebpour and Alcherio Martinoli
DISAL, EPFL, Switzerland

Five robots maintain a coverage of 100 units in a rectangular environment with two obstacles.

2017 IEEE International Conference on Robotics and Automation
Sampling-based approximate optimal temporal logic planning
Lening Li and Jie Fu
Robotics Engineering, Worcester Polytechnic Institute, USA

- A sampling-based, joint planning and control method under temporal logic constraints.
- Scalable control design based on the principal of approximate policy iteration in hybrid systems.
- Efficient, near-anytime policy search using importance sampling.

Toward Robust, Whole-hand Caging Manipulation with Underactuated Hands
Raymond R. Ma, Walter G. Bircher, and Aaron M. Dollar
Department of Mechanical Engineering and Materials Science
Yale University, USA

- Caging manipulation avoids object ejection without detailed knowledge about contact conditions or sensor feedback.
- We derived object energy fields that show where objects will move in a caging grasp.
- We present experimental object workspaces for a variety of object geometries with an underactuated hand.
- Even after regularly breaking finger contact, an object can be repeatedly manipulated without ejection.
**Lidar-histogram for fast road and obstacle detection**

Liang Chen, Jian Yang and Hui Kong  
School of Computer Science and Engineering, Nanjing University of Science and Technology, China

- Lidar-histogram integrates the detection of traversable road regions, obstacles into one single framework.
- Lidar-imagery is used to index, describe and store Lidar data.
- The problem of detecting traversable road and obstacles is converted into a simple linear classification task in 2D space.

**Vote3Deep: Fast Object Detection in 3D Point Clouds Using Efficient Convolutional Neural Networks**

Martin Engelcke, Dushyant Rao, Dominic Zeng Wang,  
Chi Hay Tong, Ingmar Posner  
Oxford Robotics Institute, University of Oxford, United Kingdom

- Vote3Deep employs CNNs to perform object detection in point clouds natively in 3D.
- Convolutions are recast as data-efficient voting operations to exploit the sparsity in the input.
- An L1 regulariser further increases the sparsity in intermediate representations and improves detection speed.
- Vote3Deep outperforms all previous state-of-the-art methods on the popular KITTI Object Detection benchmark.

**A deep representation for depth images from synthetic data**

Fabio Maria Carlucci and Paolo Russo and Barbara Caputo  
DIAG, Sapienza University, Italy  
fabiom.carlucci@dis.uniroma1.it  
https://sites.google.com/site/vandaldepthnet/  
Sample models from the VANDAL database

- We hand picked 9,383 CAD models, matching 319 ILSVRC14 classes.
- Used them to build a synthetic dataset of over 4 million depth renderings.
- We trained the DepthNet on this data and tested it on real datasets.
- First-off-the-shelf features for object classification in the Depth modality.

**A Deep Learning Approach to Traffic Lights: Detection, Tracking, and Classification**

Karsten Behrendt, Libor Novak, Rami Botros  
Bosch Automated Driving

- Bosch Small Traffic Lights Dataset with more than 24,000 traffic lights at http://k0b.de/bstld.
- Deep learning based detection, tracking, and classification.
- Real-time detections of traffic lights down to 3 pixels in width.
- Video of the results on the test-set available at http://k0b.de/tld_icra.
Multi-view Self-supervised Deep Learning for 6D Pose Estimation in the Amazon Picking Challenge

Andy Zeng¹, Kuan-Ting Yu², Shuran Song¹, Daniel Suo¹
Ed Walker³, Alberto Rodriguez², Jianxiong Xiao⁴
¹Princeton University, ²Massachusetts Institute of Technology
³Google, ⁴AutoX

- We present a robust vision approach for 6D object pose estimation from multi-view RGB-D images.
- To enable this approach, we propose a scalable, self-supervised method for automatically collecting large-scale pixel-accurate object segmentation ground truth.
- The approach was part of the MIT-Princeton Team system that took 3rd and 4th place at the Amazon Picking Challenge 2016.

Self-Paced Cross-Modality Transfer Learning for Efficient Road Segmentation

Weiyue Wang¹, Naiyan Wang², Xiaomin Wu³, Suya You¹
And Ulrich Neumann¹
¹ USC ² TuSimple ³ University of Petroleum, China

- We transfer rich scene structure inside stereo images to single RGB image without human labeling.
- Our framework can yield satisfied results with only several hundred of annotated images, and ranks 1st on KITTI road benchmark.
Autonomous Vehicle
Chair Seung-Woo Seo, Seoul National University
Co-Chair Yonghoon Ji, The University of Tokyo

14:45–14:50 TUC4.1

Predictive Positioning and Quality Of Service Ridesharing for Campus Mobility On Demand Systems
Justin Miller and Jonathan P. How
Aeronautics and Astronautics, MIT, USA
• Goal: Improve customer quality of service (QoS) for campus MOD systems.
• Predictive positioning identifies key fleet positions which minimize expected customer wait time.
• Ridesharing algorithm improves customer service times when arrival rates are high.
• Customer ratings model learns customer preference from 5-star rating feedback.

14:55–15:00 TUC4.3

Global Outer-Urban Navigation with OpenStreetMap
Benjamin Suger and Wolfram Burgard
Department of Computer Science, University of Freiburg, Germany
• We present an approach to use OpenStreetMap (OSM) as the global map for outer-urban autonomous navigation.
• The approach needs to deal with errors of the map and from the positioning sensors.
• We explore semantic terrain information to infer the position of subgoals in the local frame.
• Experiments are performed on a real robot that autonomously navigates at previously unseen locations.

14:50–15:05 TUC4.2

Toward Human-like Lane Following Behavior in Urban Environment with a Learning-based Behavior-induction Potential Map
Chunzha Guo, Takashi Owaki, Kiyosumi Kidono, Takashi Machida, Ryuta Terashima and Yoshiko Kojima
Toyota Central R&D Labs., Inc., Japan
• Improved DNN-based algorithm for detecting surrounding cars.
• Bayesian network model for classifying cars w.r.t. different states of operation.
• Learning-based instance-level behavior-induction potential map for generating human-like local path along a predefined route.

15:00–15:05 TUC4.4

Accurate Stereo Visual Odometry With Gamma Distributions
Ruben Gomez-Ojeda, Francisco-Angel Moreno, Javier Gonzalez-Jimenez
MAPIR Group, University of Malaga, Spain.
• Typically, visual odometry is solved by minimizing keypoint projection residuals between frames.
• Residuals are usually modeled with Gaussian and t-distributions, but these models are not accurate enough.
• Proposal: robust probabilistic model for the magnitude of the residuals based on Gamma distributions (better model for the data).
• Experimental validation with synthetic and real data (applied to stereo VO).

15:05–15:10 TUC4.5

Direct Visual-Inertial Navigation with Analytical Preintegration
Kevin Eckenhoff, Patrick Geneva, and Guoquan Huang
University of Delaware
• Visual-inertial navigation: estimate the trajectory of a robot equipped with cameras and IMU.
• IMU data processed through closed-form solutions of the “preintegrated” measurement equations.
• Camera data processed through direct visual alignment of stereo image pairs.
• Measurements fused in a graph-setting for trajectory solution.

15:10–15:15 TUC4.6

A Learning-Based Framework for Handling Dilemmas in Urban Automated Driving
Sang-Hyun Lee and Seung-Woo Seo
Electrical and Computer Engineering, Seoul National University, Korea
• We introduce a learning-based framework that allows automated vehicles to tackle dilemmas in urban environments.
• A driving strategy of expert drivers provides the key insight behind our work.
• The proposed framework is based on maximum entropy inverse reinforcement learning and Gaussian process.
• We demonstrate that the proposed framework yields trajectories similar to those of expert drivers.
Automated Generation of Diverse and Challenging Scenarios for Test and Evaluation of Autonomous Vehicles

Galen Mullins¹, Paul Stankiewicz², and Satyandra K. Gupta³

¹,²Johns Hopkins Applied Physics Laboratory, USA
³Aerospace and Mechanical Engineering, University of Southern California, USA

• Introduces a test case generation strategy based upon discovering performance boundaries.
• An adaptive sampling strategy is utilized to minimize the number of simulation runs required to find the performance boundaries.
• Unsupervised density-based clustering algorithms are deployed to generate a test suite composed of boundary cases.

Lane-Change Detection Based on Vehicle-Trajectory Prediction

Hanwool Woo, Yonghoon Ji, Hitoshi Kono, Yusuke Tamura, Atsushi Yamashita, and Hajime Asama

Department of Precision Engineering, University of Tokyo, Japan

Yasuhide Kuroda, Takashi Sugano, and Yasunori Yamamoto

Mazda Motor Corporation, Japan

• We improved the detection accuracy by using a vehicle-trajectory prediction.
• Our approach considers the possibility of crashes during a lane change.
• A trajectory is predicted by using a potential field method.
• The trajectory prediction adopts the result of driving-intention estimation and generates potential fields.

Examples of performance boundaries for a simple navigation scenario.

Result of trajectory prediction.
Distributed Robot Systems 1
Chair Paolo Robuffo Giordano, Centre National de la Recherche Scientifique (CNRS)
Co-Chair Mac Schwager, Stanford University

14:45–14:50 TUC5.1

Distributed Algo. for Mapping the Graphical Struct. of Complex Envs. w/ a Swarm of Robots

Adam Caccavale
Department of Mechanical Engineering, Stanford University, U.S.A.

• Swarms of simple robots deployed to discover graphical structure of environment
• Robots have bump sensors, GPS, highly limited memory, and range-limited communication network
• Robots build graph through exploration and communication with neighbors
• Algorithm is distributed, scalable, and all robots achieve the true underlying graph in finite time

Robots Converging on Graphical Environment Model

14:50–14:55 TUC5.2

Bearing Rigidity Maintenance for Formations of Quadrotor UAVs

Fabrizio Schiano1, and Paolo Robuffo Giordano2
1INRIA Rennes, France, 2CNRS Rennes, France

• Control of a formation of quadrotor UAVs equipped with onboard cameras
• Several sensing constraints taken into account: (a) maximum/minimum range of the camera, (b) limited fov of the camera, (c) possible occlusions between the agents
• Decentralized gradient-based controller for maintaining bearing rigidity of the formation
• Real experiments with 5 quadrotor UAVs

14:55–15:00 TUC5.3

A Portable, 3D-Printing Enabled Multi-Vehicle Platform for Robotics Research and Education

Jingjin Yu, Shuai D. Han, Wei N. Tang
Department of Computer Science, Rutgers University, USA
Daniela Rus
Computer Science and Artificial Intelligence Lab, MIT, USA

• An affordable, portable, and open source micro-scale mobile robot platform – microMVP
• 3D-printing enabled design
• Robust performance
• Support centralized or distributed methods
• More information http://arc.cs.rutgers.edu/mvp

15:00–15:05 TUC5.4

Minimum-violation scLTL motion planning for mobility-on-demand

Cristian-Ioan Vasile1, Jana Tumova2, Sertac Karaman1, Calvin Bela3 and Daniela Rus1
1Massachusetts Institute of Technology, USA
2Department of Robotics, Perception, and Learning, KTH, Sweden
3Department of Mechanical Engineering, Boston University, USA

• Road network and autonomous vehicle with limited sensing
• Transportation request (minimize delay) + Rules of the road (minimize violation) + User safety preference (strictly enforced) - scLTL
• Problem: Find a control policy that minimizes the total violation penalty
• Solution: combined motion and route planning

15:05–15:10 TUC5.5

Duckietown: an Open, Inexpensive and Flexible Platform for Autonomy Education and Research

Liam Pauli, Jacopo Tani, Heejin Ahn, Javier Alonso-Mora, Luca Carlone, Michael Cap, Yu Fan Chen, Changhyun Choi, Jeff Duarte, Yajun Fang, Daniel Hoehener, Shih-Tye Liu, Michael Novitzky, Igor Franzoni Okuyama, Jason Pauls, Guy Rosenman, Valerio Varricchio, Huei-Cheng Wang, Dmitry Vendrty, Hang Zhou, Michael Benjamin, Christopher Carr, Maria Zubir, Sertac Karaman, Emilio Frazzoli, Dominika Denicol, Daniela Rus, Jonathan Hor, John Leonard, Andrea Censi
Massachusetts Institute of Technology

• An educational, research, and outreach effort
• Duckietown is inexpensive yet capable and realistic (follow lanes, avoid objects, navigate, coordinate)
• All of the materials have been released open source, see duckietown.mit.edu for details

15:10–15:15 TUC5.6

Duckietown is an autonomous mobility-on-demand service for duckies

2017 IEEE International Conference on Robotics and Automation
Decentralized Coordinated Motion for a Large Team of Robots Preserving Connectivity and Avoiding Collisions

Anqi Li, Wenhao Luo, Sasanka Nagavalli and Katia Sycara
Robotics Institute, Carnegie Mellon University, USA

- **Goal:** Coordination of a group of robots towards a goal region while avoiding collisions and ensuring connectivity
- Capable of avoiding deadlock in cluttered environment
- Scalable as the number of robots grows
- Robust to insertion and deletion of individual robot

Intercepting Rogue Robots: An Algorithm for Capturing Multiple Evaders with Multiple Pursuers

Alyssa Pierson¹, Zijian Wang², and Mac Schwager²
¹Dept. of Mechanical Engineering, Boston University, USA
²Dept. of Aero/Astro, Stanford University, USA

- Guaranteed capture of multiple evaders in finite time by one or more pursuer in $\mathbb{R}^2$
- Pursuers use “Area-minimization” strategy, utilize properties of Voronoi tessellation
- Agnostic to evader control policy
- Experiments with Ouijabots and GoPiGo robots running controllers on-board
Efficient Learning of Constraints and Generic Null Space Policies

Leopoldo Armesto
Universitat Politecnica de Valencia, Spain
Jorren Bosga and Vladimir Ivan and Sethu Vijayakumar
University of Edinburgh, United Kingdom

• We applied RLT* to social navigation tasks for
  • We decompose observations into task-null-
  • Our method outperforms the state of art in
  • The learnt policy generalizes across different
  • Experimental setup: we train a model on

See our video for the complete experiment setup

Supervisory teleoperation with online learning and optimal control

Ioannis Havoutis1,2 and Sylvain Calinon1
1 Idiap Research Institute, Martigny, Switzerland
2 Oxford Robotics Institute, University of Oxford, United Kingdom

• Learning from demonstration (LfD) applied to
• Online Bayesian nonparametric learning of task-
• On the operator’s side, the model is build based
• The model is used to autonomously complete the
task using model predictive control (MPC) and
• Results suggest that RLT* performs and scales
better than the baseline method, Maximum
Margin Planning.

Rapidly Exploring Learning Trees

Kyrilacos Shiari Is Ioannis Messias
Institute of Informatics, Amsterdam, The Netherlands
Shimon Whiteson
Department of Computer Science, University of Oxford, UK

• Rapidly Exploring Learning Trees (RLT*) learns
RRT* cost functions from demonstrations.
• A caching scheme makes learning faster and
more effective.
• We apply RLT* to social navigation tasks for
real and simulated mobile robots.
• Results suggest that RLT* performs and scales
better than the baseline method, Maximum
Margin Planning.

Virtual vs. Real: Trading Off Simulations and Physical Experiments in Reinforcement Learning with Bayesian Optimization

Alonso Marco1, Felix Berkenkamp2, Philipp Hennig3, Angela P. Schoellig4,
Andreas Krause2, Stefan Schaal1, and Sebastian Trimpe5
1 Autonomous Motion Department, MPI for Intelligent Systems, Germany
2 Learning & Adaptive Systems Group, ETH Zurich, Switzerland
3 Dynamic Systems Lab, University of Toronto, Canada

• Tuning controller gains is frustrating and
• Simulations: cheap, inaccurate.
• Physical experiments: expensive, accurate.
• Entropy-based Bayesian Optimizer
alternatively selects the most
informative source per unit of cost,
saving unnecessary physical
experiments.
Learning and Adaptive Systems 3

Chair Gakuto Masuyama, Chuo University
Co-Chair Ioannis Havoutis, Idiap Research Institute

15:15–15:20 TUC6.7

COCoMoPL: A Novel Approach for Humanoid Walking Generation Combining Optimal Control, Movement Primitives and Learning and its Transfer to the Real Robot HRP-2
Debora Clever, Monika Harant, Katja Mombaur
Interdisciplinary Center for Scientific Computing, University of Heidelberg, Germany
Maximilien Naveau, Olivier Stasse
CNRS - LAAS, Toulouse, France
Dominik Endres
Theoretical Neuroscience Group, Dept. Psychology, Philipps-University Marburg, Germany

- Use optimal control and detailed HRP-2 roboc model to compute optimal and dynamically feasible walking motions
- Learn morphable movement primitives based on Gaussian processes and principal component analysis
- COCoMoPL leads to nearly optimal movements, which can be feasible on a real robot, here HRP-2.

Gait generation using movement primitives learned from optimal control based motions

15:20–15:25 TUC6.8

Repeatable Folding Task by Humanoid Robot Worker using Deep Learning
Pin-Chu Yang1 and Shigeki Sugano3
Department of Modern Mechanical Engineering, Waseda University, Japan
Kazuma Sasaki2, Kanata Suzuki2, Kei Kase4 and Tetsuya Ogata6
Department of Intermedia Art and Science, Waseda University, Japan

- Humanoid Robot + Deep Learning: = Ideal F.A. Solution for Complex Task
- Reiterating Soft Object Folding Motion: = Long & Repeatable Task Performable
- End-to-End Training with Teleoperation: = Easy to Train and Apply

Robot performing folding task through Deep Learning
**Grasping 1**

Chair Amir Shapiro, Ben Gurion University of the Negev  
Co-Chair Lorenzo Natale, Istituto Italiano di Tecnologia

**A Grasping Approach Based on Superquadric Models**  
Giulia Vezzani, Ugo Pattacini and Lorenzo Natale  
iCub Facility, Istituto Italiano di Tecnologia, Italy  
University of Genova, Italy

- Grasping of unknown objects  
- The object and the volume graspable by the hand are modeled with superquadric functions  
- Pose computation is formulated as a nonlinear constrained optimization problem  
- The method computes poses suitable also for grasping small objects, while avoiding hitting the table with fingers and taking into account also object portions occluded by vision

**Grasp Qualification Done Right**  
Robert Krug  
AASS Research Center, Örebro University, Sweden  
Yasemin Bekiroglu  
Corporate Research, ABB AB, Sweden  
Maximo A. Roa  
Institute of Robotics and Mechatronics, DLR, Germany

- We study the influence of sum-magnitude and independent grasp contact force bounds.  
- We empirically show that grasp quality metrics are often severely underestimated.  
- The work highlights the importance of task-based quality assessment.  
- Our findings are based on a large set of real-world grasps.

**A Hybrid Deep Architecture For Robotic Grasp Detection**  
Di Guo, Fuchun Sun, Huaping Liu, Tao Kong, Bin Fang  
Tsinghua University, Beijing, China  
Ning Xi  
University of Hong Kong, Hong Kong, China

- A novel hybrid deep architecture is proposed for real world robotic grasp detection.  
- A THU grasp dataset is collected on a real robotic platform.  
- The dataset contains the visual information, tactile information and grasp configurations.

**Control of Linear and Rotational Slippage Based on Six-axis Force/Tactile Sensor**  
Andrea Cirillo, Pasquale Cirillo, Giuseppe De Maria  
Ciro Natal, Salvatore Pirozzi, DIII, Università degli Studi della Campania «L. Vanvitelli», Italy

- Sensorized gripper with a six-axis force/tactile sensor.  
- Measurement of both object orientation and six components of the applied wrench.  
- Control strategy for avoiding both linear and rotational slipping in dynamic conditions.  
- Experimental results of dynamic slipping avoidance in presence of uncertainties

**Supervision via Competition: Robot Adversaries for Learning Tasks**  
Lerrel Pinto, James Davidson and Abhinav Gupta  
Carnegie Mellon University, Google

- We propose an adversarial framework for effective self-supervised learning and demonstrate for grasping objects.  
- We show improvement from 68% without adversaries to 82% grasping accuracy with adversaries like shaking and snatching.  
- We also demonstrate that robots in adversarial setting might be better than collaborative robots.

**A Cloud Robot System Using Dex-Net and Berkeley Robotics and Automation as a Service (Brass)**  
Nan Tian*, Matthew Matti*, Jeffrey Mahler, Yu Xiang Zhou, Samantha Staszak, Christopher Correa, Steven Zheng, Qiang Li, Robert Zhang, Ken Goldberg  
UC Berkeley AUTOLAB Berkeley CA, USA

- Increases grasp reliability over locally-computed grasping strategies.  
- Network latencies of 30 and 200 msec for servers 500 and 6000 miles away, respectively.  
- Execution reports from robots in the field update grasp recommendations over time.
Modeling Grasp Motor Imagery though Deep Conditional Generative Models

Matthew Veres, Medhat Moussa and Graham W. Taylor
School of Engineering, University of Guelph, Canada

- Grasping is dependent on extrinsic and intrinsic object properties (e.g. geometry, surface friction)
- Grasping follows a many-to-many mapping between objects and actions
- Hypothesis: possible to learn integrated object-action representations for grasping
- Deep conditional generative models can learn to generate grasps following multi-modal distributions

Grasping objects using multiple grasping modes

Caging Polygonal Objects Using Equilateral Three-Finger Hands

H. A. Bunis and E. D. Rimon
Dpt. of Mechanical Engineering, Technion, Israel
Y. Golan and A. Shapiro
Dpt. of Mechanical Engineering, Ben-Gurion University, Israel

- Three-finger robot hands in equilateral triangle finger formations are used to cage polygonal objects.
- While the configuration space of such hands is four dimensional, their contact space is only two-dimensional.
- The paper describes a caging graph that is constructed in the hand’s contact space.
- The caging graph can be searched for three-finger caging regions surrounding the object.

Top: A three-finger robot hand. Bottom: its contact space and caging graph
Human-Robot Interaction 2

Chair Ko Ayusawa, AIST
Co-Chair Jaime Valls Miro, University of Technology Sydney

14:45–14:50 TUC8.1

Show, Attend and Interact: Perceivable Human-Robot Social Interaction through Neural Attention Q-Network

A. H. Qureshi, Y. Nakamura, Y. Yoshikawa & H. Ishiguro
Department of System Innovation, Osaka University, Japan

• This paper introduces the Neural Attention Q-Network using which the robot learned human-like social interaction skills through interaction with people in uncontrolled real environments.

• The results indicate that the robot has learned to respond to complex human behaviors in a perceivable and socially acceptable manner.

15:00–15:05 TUC8.5

Learning Social Affordance Grammar from Videos: Transferring Human Interactions to Human-Robot Interactions

Tianmin Shu1, Xiaofeng Gao2, Michael S. Ryoo3 and Song-Chun Zhu1
1University of California, Los Angeles, USA 2Fudan University, China 3Indiana University, Bloomington, USA

• A general framework for learning social affordance grammar as a spatiotemporal AND-OR graph (ST-AOG)

• Weakly supervised learning from RGB-D Videos

• Real-time motion inference and motion transfer from human interactions to human-robot interactions

• Simulations and real Baxter tests were performed to evaluate our system

14:50–14:55 TUC8.2

Two-Eye Model-Based Gaze Estimation from A Kinect Sensor

Xiaolong Zhou
College of Computer Science and Technology, Zhejiang University of Technology, China
Haibin Cai and Honghai Liu
School of Computing, University of Portsmouth, UK
Youfu Li
Dept. of Mechanical and Biomedical Engineering, City University of Hong Kong, China

• An effective gaze estimation method based on two-eye model with accuracy is about 1.96º

• An improved convolution-based means of gradients iris center localization method

• A new personal calibration method based on a simplified eye model

• The proposed gaze estimation method outperforms many leading methods in the state-of-the-art

15:05–15:10 TUC8.6

Emotional Intelligence in Robots: Recognizing Human Emotions from Daily-Life Gestures

Mohammad Reza Loghmani
ACIN, Vienna Univ. Of Tech., Austria

Stefano Rovetta
DIBRIS, University of Genoa, Italy

Gentiane Venture

Tokyo Univ. of Agric. And Tech., Japan

• Recognize emotions from non-stylized body gestures

• Multi-sensor system based on commercial sensors: Microsoft Kinect, Wii Balance Board, IMU Shimmer

• Two-stage algorithm based on Recurrent Neural Networks

14:55–15:00 TUC8.3

ModLight: Designing a Modular Light Signaling Tool for Human-Robot Interaction

Elizabeth Cha, Tushar Trehon, Lancelot Watthieu, Christian Wagner, Anurag Shukla and Maja Mataric
Computer Science, University of Southern California, USA

• Recent work has shown the promise for light-based communication for robots.

• The large design space of light communication as well as the large range of robots and applications presents unique challenges for researchers.

• In this work, we present the design of ModLight, a modular research tool consisting of a set of low cost light blocks, that can be easily reconfigured to fit various platforms, and a software library.

15:10–15:15 TUC8.4

Towards Real-Time 3D Sound Sources Mapping with Linear Microphone Arrays

Daobilige Su, Teresa Vidal-Calleja and Jaime Valls Miro
Centre for Autonomous Systems, University of Technology Sydney, Australia

• Multi hypotheses tracking is combined with a new sound source parametrisation to provide with a good initial guess for an online optimisation strategy

• A dedicated sensor model is proposed to accurately model the noise of the DOA observation when using a linear microphone array.

• A joint optimisation is carried out to estimate 6 DOF sensor poses and 3 DOF landmarks together with sound sources locations.

2017 IEEE International Conference on Robotics and Automation
Modeling Cooperative Navigation in Dense Human Crowds

Anirudh Vemula, Katharina Muelling and Jean Oh
Robotics Institute, Carnegie Mellon University, USA

- Model velocity conditioned on goal and occupancy grid, using gaussian processes to fit observed data
- Infer goal from set of known goals using learned model and observed part of trajectory
- Predict future trajectories by sampling velocities from model using multi-step Monte Carlo
- Learned model captures behavior such as cooperative navigation and collision avoidance

Coordination Dynamics in Multi-human Multi-robot Teams

Tariq Iqbal and Laurel D. Riek
Department of Computer Science and Engineering, University of California San Diego, USA

- We investigate how the presence of robots affects group coordination when both the anticipation algorithms they employ and their number vary.
- Results suggest that group coordination is significantly affected when a robot joins a human-only group.
- It is further affected when a second robot joins the group and employs a different anticipation algorithm from the other robot.

Three participants danced together with two robots.
The Robotarium: A remotely accessible swarm robotics research testbed

Daniel Pickem, Paul Glotfelter, Li Wang, Mark Mote, Aaron Ames, Eric Feron, Magnus Egerstedt
Georgia Institute of Technology

Goal: Enable safe remote access to large numbers of robots!

- Provides remote access to state-of-the-art multi-robot facility
- Automates experiment execution and maintenance of robots
- Provides built-in minimally invasive safety mechanisms
- Is accessible through web interface

Design, Development and Experimental Assessment of a Robotic End-effector for Non-standard Concrete Applications

N. Kumar, J. Buchli: ADRL, ETH Zurich, Switzerland
N. Hack, K. Doerfler, A. Walzer, F. Gramazio, M. Kohler: ITA, ETH Zurich
G. Rey: MOOG Inc., USA

- A novel robotic construction technique called Mesh Mould Metal has been prototyped
- Saves material, allows greater geometric freedom, fabricates metal meshes to act as reinforcement and formwork
- A robotic end-effector has been custom designed to execute the fabrication process
- Preliminary experiments leading to fabrication of single curved and double curved metal meshes

Information Theoretic MPC for Model-Based Reinforcement Learning

Grady Williams, Nolan Wagener, Brian Goldfain, Paul Drews, James M. Rehg, Byron Boots, and Evangelos A. Theodorou
Institute for Robotics and Intelligent Machines
Georgia Institute of Technology, USA

- We introduce an information theoretic model predictive control (MPC) algorithm.
- The algorithm is capable of handling non-linear dynamics and complex cost criteria.
- We apply the algorithm to reinforcement learning tasks by learning models with deep neural networks.
- We demonstrate the capability of the method in simulation and in a real-world aggressive driving task.

Estimating unknown object dynamics in human-robot manipulation tasks

D. Cehajic, P. Budde gen. Dohmann and S. Hirche
Technical University of Munich, Germany

- Estimation strategy for identifying unknown object dynamics avoiding undesired human interaction wrenches
- Identification-relevant motions derived such to excite the estimator
- Identification motions projected in the null space of the partial grasp matrix relating the human and robot
- Experimental validation in a human-robot cooperative object manipulation setting
A Framework for Sensorless and Autonomous Probe-Tissue Contact Management in Robotic Endomicroscopic Scanning

Rejin John Varghese, Pierre Berthet-Rayne, Petros Giataganas, Valentina Vitiello, Guang-Zhong Yang
The Hamlyn Centre for Robotic Surgery, Imperial College London, UK

- Robotic endomicroscopy framework for real-time in-vivo tissue characterization
- Sensorless probe-tissue contact management based on real-time image analysis
- Optimal contact maintained using model-free controller based on reinforcement learning
- Experimental results demonstrate near real-time ability to resolve both loss-of-contact and excess-deformation scenarios

RAFS: a computer-assisted robotic system for minimally invasive joint fracture surgery, based on pre- and intra-operative imaging

Giulio Dagnino, Ioannis Georgilas, Samir Morad, Peter Gibbons, Payam Tarassoli, Roger Atkins, and Sanja Dogramadzi
Bristol Robotics Laboratory, Bristol, UK

- Simultaneous manipulation of two fragments;
- Lower limb traction capability;
- Full pre-operative surgical planning (virtual reduction);
- Intra-operative real-time 3D image guidance;
- Enhanced clinical workflow;
- Preliminary cadaveric trials provided positive outcome pointing to the RAFS system usability in the operating theatre.

Towards Active Variable Stiffness Manipulators for Surgical Robots

Huu Minh Le, Cao Lin, and Soo Jay Phee
Robotics Research Centre, School of MAE, NTU, Singapore.
Thanh Nho Do
California NanoSystems Institute, University of California, Santa Barbara, Elings Hall, Mesa Road, Goleta, USA

- Simple variable stiffness design using PET tube and stainless steel flexible sheath;
- Experiments show the promising results: this VST can be more flexible or stiffer than a typical endoscope;
- Modelling, control, and application design problems will be addressed in the future works.

Controlling the Stormram 2: An MRI-compatible Robotic System for Breast Biopsy

Mohamed E. M. K. Abdelaziz, Vincent Groenhuis, Françoise Siepel, Stefano Stramigioli
Robotics and Mechatronics, University of Twente, The Netherlands
Jeroen Veltman
Ziekenhuisgroep Twente, The Netherlands

- Compact pneumatically-actuated 5 DOF MRI-compatible breast biopsy robot was developed and controlled by a computerized valve manifold;
- Accuracy/efficiency measurements are performed using 2 different breast phantoms inside 0.25T MRI scanner;
- Developed robotic system has potential to perform MRI-guided breast biopsies accurately and improve clinical workflow.

EEG-Controlled Meal Assistance Robot with Camera-Based Automatic Mouth Position Tracking and Mouth Open Detection

Chamika Janith Perera and Thilina Dulantha Lalitharatne
Department of Mechanical Engineering, University of Moratuwa, Sri Lanka
Kazuo Kiguchi
Department of Mechanical Engineering, Kyushu University, Japan

- This paper proposes an EEG-SSVEP-based controlled Meal Assistance Robot with camera-based automatic mouth position tracking and automatic mouth open/closed detection system;
- User selects the desired food item by looking at the corresponding flickering LED panel and the user intention is recognized using EEG-SSVEP signals;
- Automatic mouth position tracking method is used to align the spoon along with the mouth and mouth open/closed identification is used to feed the food when user is ready to consume.

Effects of Exoskeleton Weight and Inertia on Human Walking

Xin Jin, Yusheng Cai, Antonio Prado and Sunil K. Agrawal
Dept of Mechanical Engineering, Columbia University, USA

- An improved design of Cable-driven Active Leg Exoskeleton (C-ALEX, right figure) was made;
- Besides being light-weight and joint-free, the new C-ALEX also has large joint RoM and no restriction to the pelvic motion;
- An experiment using C-ALEX was performed to investigate the effect of exoskeleton weight and inertia on natural gait;
- The result showed weight and inertia each has their unique effect, suggesting a light-weight design can better preserve the natural gait
Enhancing Seated Stability Using Trunk Support Trainer (TruST)
Moiz Khan, Jiyeon Kang, Brian Bradley, and Sunil Agrawal
Mechanical Engineering, Columbia University, USA
Victor Santamaria and Andrew Gordon
Teachers College, Columbia University, USA
Joseph Dutkowsky
Orthopedic Surgery, Columbia University Medical Center, USA
• Our group has developed the first active posture training robot (TruST).
• It can apply assistive or resistive forces/moments, provide multi-directional perturbations, and provide a force-tunnel.
• We use an assist-as-needed force strategy to train posture at the boundary of stability.
• A single session training with TruST significantly increases lower trunk and pelvis translations and rotations.

Developing a Compact Robotic Needle Driver for MRI-Guided Breast Biopsy in Tight Environments
D Navarro-Alarcon, S Singh, T Zhang, HL Chung
KW Ng, MK Chow, YH Liu
Dept. of Mechanical and Automation Engineering, CUHK, Hong Kong SAR
Time Medical Limited, Hong Kong SAR
• We developed a new 3-DOF robot for MRI-guided breast biopsy.
• The robot’s structure, sensors, and actuators are MRI-compatible.
• Two piezo-electric motors align the needle’s axis with the lesion.
• A pneumatic cylinder drives the needle into the breast tissues.
Industrial Robots

Chair William R. Hamel, University of Tennessee
Co-Chair Liao Wu, Queensland University of Technology

14:45–14:50 TUC11.1
Real Time Welding Parameter Prediction for Desired Character Performance
Hang Dong and Ming Cong
Dalian University of Technology, China
Yukang Liu and Yuming Zhang
University of Kentucky, USA
Heping Chen
Texas State University, USA

• Use Gaussian Process Regression to model the Dynamic weld poor Character Performance.
• Use Bayesian Optimization to predict robust welding parameters.
• Use performance measurement system to obtain experiment data.
• The prediction results are detailed.

14:50–14:55 TUC11.2
An Ultra-Compact Infinitely Variable Transmission for Robotics
Alexander S. Kernbaum, Murphy Kitchell and Max Crittenden
SRI Robotics, SRI International, USA

• Small enough it can be used in many robotic applications where previously not possible.
• Output direction can invert while maintaining constant input direction.
• Can be used for significant energy savings by aligning the motor speed with its peak efficiency or by recovering kinetic energy from robot motions.
• Potential applications in haptics and human-safe robotics

14:55–15:00 TUC11.3
Toward controlling a KUKA LBR IIWA for interactive tracking
Vinay Chawda and Günter Niemeyer
Disney Research Los Angeles, USA

• KUKA’s Fast Robot Interface (FRI) is used to design and implement a tracking controller on the Lightweight Robot (LBR) IIWA.
• Internal torque control structure and its characteristics are identified to design controllers of varying complexity.
• Using full state feedback, we achieve smooth and good tracking of the unsensed link positions.

15:00–15:05 TUC11.4
ICRA 2017 Digest
Quick Positional Health Assessment for Industrial Robot Prognostics and Health Management (PHM)
Guixiu Qiao, Craig Schlenoff, and Brian A. Weiss
National Institute of Standards and Technology (NIST), USA

• A subset of PHM research involves developing a quick health assessment methodology emphasizing the identification of the positional health (position and orientation accuracy) changes.
• NIST’s effort to develop the measurement science to support this development, including the modeling and algorithm development for the test method, the advanced sensor development to measure 7-D information (time, X, Y, Z, roll, pitch, and yaw), algorithms to analyze the data, and a use case to present the results.

15:05–15:10 TUC11.5
Automatic Robot Taping with Force Feedback
Yilong Yuan
School of Electro-Mechanical Engineering, Foshan Univ., China
Teguh Santoso Lemborno
Engineering Product Development, SUTD, Singapore
T-Ming Chen
School of Mechanical and Aerospace Engineering, NTU, Singapore.
Simon Nelson Landén, Victor Malmgren
School of Industrial Engineering and Management, KTH, Sweden.

• An automatic robotic taping system for surface protection through attaching masking tapes.
• The taping path planning method apply 3D scanning model to generate the surface covering trajectory.
• Specific taping end-effectors are designed to enable tape attachment, force control and cutting.
• A very useful taping package for surface protection before painting, plasma spraying etc..

15:10–15:15 TUC11.6
Dexterity Analysis of Three 6-DOF Continuum Robots Combining Concentric Tube Mechanisms and Cable Driven Mechanisms
Liao Wu, Ross Crawford, and Jonathan Roberts
Australian Centre for Robotic Vision
Science and Engineering Faculty, Queensland University of Technology, Australia

• We investigated the dexterity of three continuum robots by introducing indices based on the concept of orientability.
• Results imply that evenly allocating degrees of freedom (DOFs) among the segments achieves the best workspace and dexterity.
• Otherwise, assigning more DOFs to the proximal segment tends to enlarge the workspace and adding more DOFs to the distal segment tends to improve the dexterity.
Compensation of Load Dynamics for Admittance Controlled Interactive Industrial Robots using a Quaternion-based Kalman Filter

Saverio Farsoni, Marcello Bonfè
Engineering Department, University of Ferrara, Italy
Chiara Talignani Landi, Federica Ferraguti, Cristian Secchi
DISMI, University of Modena and Reggio Emilia, Italy

- Human inputs, applied to F/T sensors on interactive robots, can be distinguished from load dynamic effects only with an accurate estimation of load accelerations/velocities
- We propose a novel estimation approach using a Quaternion-based Kalman filter and only pose measurements (available from any industrial robot controller)
- Experiments demonstrate the superiority of our approach w.r.t. to numerical differentiation and inertial measurements

Comparative Study of Serial-Parallel Delta Robots with Full Orientation Capabilities

J. Brinker¹, N. Funk¹, P. Ingenlath¹, Y. Takeda², and B. Corves¹
¹ Dept. of Mechanism Theory and Dyn. of Machines, RWTH Aachen, DE
² Dept. of Mechanical Engineering, Tokyo Institute of Technology, JP

- By functionally extending the Delta robot, commercial concepts obtain up to three additional rotational dof
- Even though the complexity is higher, energy-based dynamic models can be solved in reasonable times
- Energy efficiency of $E_F$ is superior, whereas $E_{DL}$ does not incorporate telescopic members
- $E_{DL}$ equally obtains reasonable results in respect of energy consumption and torques
Biomimetic robotic joint mechanism driven by soft linear actuators
Kyeong Ho Cho, Min Geun Song, Hosang Jung, Sang Yil Yang, Hugo Rodrigue, Hyungpil Moon, Ja Choon Koo, and Hyouk Ryool Choi
Mechanical Engineering, Sungkyunkwan University, Korea

- Limitations of soft linear actuators
- Mimicking the working principle of skeletal muscle (sliding filament mechanism)
- Development of two types of Sliding Filament Joint Mechanisms (SFJMs)
- Verification of the feasibilities of SFJMs with shape memory alloy wires

Multi-Objective Design Optimization Of a Soft, Pneumatic Robot
Daniel Boddy and Marc Killpack
Mechanical Engineering, Brigham Young University, USA

- Genetic Algorithm used to optimize the kinematic structure of a soft, inflatable robot
- Multi-objective, maximin fitness function used to efficiently identify the Pareto front
- Designs are evaluated at many randomly generated configurations on multiple, user-defined metrics
- Link lengths and base mount of an inflatable manipulator optimized for dexterity and load lifting capacity

A Robotic Manipulator Design with Novel Soft Actuators
Xiaojiao Chen1, Jing Peng1, Jianshu Zhou1, Yonghua Chen1, Michael Yu Wang2, and Zheng Wang1,3
1Department of Mechanical Engineering, the University of Hong Kong, Hong Kong
2Department of Mechanical and Aerospace Engineering, the Hong Kong University of Science and Technology, Hong Kong
3The University of Hong Kong Shenzhen Institute of Research and Innovation (HKU-SIRI), Shenzhen, China

- Novel soft linear actuator “SHENLINDER” with maximum 300% elongation and linear force output.
- A novel 6-DOF manipulator with biomimetic kinematic structure driven by 12 SHELINDERs
- A tri-fingered soft robotic hand with continuous rotation on each finger

Electric Phase-change Actuator with Inkjet Printed Circuit For Printable and Integrated Robot Prototyping
Kenichi Nakahara, Koya Narumi, Ryuma Niyama and Yoshihiro Kawahara
Graduate School of Information Science and Technology, The University of Tokyo, Japan

- Proposes an electrically driven printable actuator
- It consists of inkjet-printed electric heater and heat-bonded nylon pouch with liquid inside
- It can be easily integrated into origami robots
- Theoretical model, fabrication process, real examples are shown in the paper

A Robotic Manipulator Design with Novel 6-DOF Soft Actuators
Van de Ven, PhD and Timothy M Kowalewski, PhD
Mechanical Engineering, University of Minnesota, USA

- For human-interactive robot systems, actuation transparency and mechanical safety are the most important requirements
- In this paper, a compact rotary series elastic actuator (cRSEA) is designed considering the actuation transparency and the mechanical safety
- The mechanical parameters of a cRSEA are selected considering the controllability, the input and output torque transmissibility, and the mechanical impedance
- Also mechanical clutch to automatically disengage the transmission is introduced

Soft robot locomotion through a tube.
- Serial Actuation
- Fiber reinforced actuators
- Optimized design for tube locomotion
Force Measurement towards the Instability Theory of Soft Pneumatic Actuators

Yi Sun, Xinquan Liang, Jiawei Cao, Marcelo H. Ang. Jr.
Dept. Mechanical Engineering, National University of Singapore, Singapore
Hong Kai Yap, Raye Chen Hua Yeow
Dept. Biomedical Engineering, National University of Singapore, Singapore

- This paper brings up the instability issue of the SPA force application with detailed description.
- A new perspective is provided to view the bending SPAs as curved beams to understand the force failing problems as instability.
- Newly-designed bending SPAs were fabricated, and measured using a less confined measuring condition.
- Material, length, pressure and measuring angle are investigated to study their effects on the buckling occurrences.

A Self-locking-type Expansion Mechanism to Achieve High Holding Force and Pipe-passing Capability for a Pneumatic In-pipe Robot

Tomonari Yamamoto, Masashi Konyo
Kenjiro Tadakuma, and Satoshi Tadokoro
Graduate School of Information Sciences, Tohoku University, Japan

- Novel concept and design to generate high holding force for in-pipe robot is proposed.
- Retractable pin mechanism to invoke self-locking phenomenon realizes high holding force and smooth pipe-passing.
- Maximum holding force, 69.7 N, was 5.2 times higher than our previous mechanism.
- Robot equipped with the proposed mechanism successfully moves through horizontal, vertical, and bent pipes.
Collision Avoidance

Chair Dinesh Manocha, University of North Carolina at Chapel Hill
Co-Chair Giuseppe Oriolo, Sapienza University of Rome

Human Body Part Multicontact Recognition and Detection Methodology
Kwan Suk Kim and Luis Sentis
Mechanical Engineering, The University of Texas at Austin, USA

- Estimate contact force, contact location, and human body part
- Multiple contacts can be detected
- Sensor fusion from 3D LiDAR and torque sensors in drivetrain
- Conceptual application example on omnidirectional mobile platform

Collision Avoidance with Limited Field of View Sensing: A Velocity Obstacle Approach
Steven Roelofsen, Alcherio Martinoli
Distributed Intelligent Systems and Algorithms Laboratory, EPFL, Switzerland
Denis Gillet
Coordination and Interaction System Group, EPFL, Switzerland

- Studies collision avoidance with sensors that have a limited field of view
- Shows that the velocity has to be constrained to a specific set because of limited field of view.
- Presents a velocity obstacle collision avoidance algorithm that satisfies the constrained sensory set.
- Validates the new collision avoidance algorithm respecting the constrained sensory set in simulation and real-world experiments.

Parallel Collision Check for Sensor Based Real-Time Motion Planning
Massimo Cefalo, Emanuele Magrini, Giuseppe Oriolo
DIAG, Sapienza University of Rome, Italy

- A real-time collision check approach built for GPU parallel computations
- Based on the visual feedback of a 2.5D image sensor
- Applied to real-time Task-Constrained Motion Planning problems
- Simulations and experiments on a real robot show the effectiveness of the method

Efficient Probabilistic Collision Detection for Non-Convex Shapes
Jae Sung Park and Chonghyun Park and Dinesh Manocha
University of North Carolina at Chapel Hill, USA
http://gamma.cs.unc.edu/PCOLLISION

- Compute the probability of collisions between two shapes, given positional error distribution
- Linearize 3D Gaussian probability distribution to compute the upper bound of collision probability
- Combine bounding volume hierarchies with collision probability bounds
- Used for real-time trajectory planning of high DOF manipulators with geometric uncertainty

Collision Avoidance with Limited Field of View Sensing: A Velocity Obstacle Approach

Human Body Part Multicontact Recognition and Detection Methodology

Parallel Collision Check for Sensor Based Real-Time Motion Planning

Efficient Probabilistic Collision Detection for Non-Convex Shapes

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Human Body Part Multicontact Recognition and Detection Methodology

Parallel Collision Check for Sensor Based Real-Time Motion Planning

Efficient Probabilistic Collision Detection for Non-Convex Shapes
Fast, On-line Collision Avoidance for Dynamic Vehicles using Buffered Voronoi Cells

Dingjiang Zhou¹, Zijian Wang², Saptarshi Bandyopadhyay³ and Mac Schwager³
¹Mechanical Engineering Department, Boston University, USA
²Aeronautics & Astronautics Department, Stanford University, USA
³Jet Propulsion Laboratory, Caltech, USA

- Distributed collision avoidance algorithm for multiple dynamic vehicles, each robot plans a path within the BVC in a receding horizon fashion.
- Algorithm has a computational complexity of O(k), comparable to ORCA, better than MPC and MPC-SCP.
- Benchmark simulation compared to ORCA.
- Experiments with five micro aerial vehicles over more than 70 trials.

Dynamical System based Robotic Motion Generation with Obstacle Avoidance

Sotiris Stavridis¹, Dimitrios Papageorgiou¹,² and Zoe Doulgeri¹,²
¹Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Greece
²Center for Research and Technology Hellas (CERTH), Greece

- Additive control input to a dynamical system for obstacle avoidance.
- Obstacle Avoidance control synthesis based on Prescribed Performance Control.
- Guarantee of stability and obstacle avoidance.
- Comparison with modulated dynamical systems and task priority framework solutions.

Experiment with KUKA LWR4+
Depth from Stereo Polarization in Specular Scenes for Urban Robotics

Kai Berger and Larry Matthies
Jet Propulsion Laboratory, USA
Randolph Voorhies
inVia Robotics, USA

- Graph-Cut approach to stereo vision with 2nd order surface normal prior
- Surface normal prior from polarization information (AOP)
- Use Micropolarizer camera to get 4 polarized images per frame, compute AOP and DOLP
- Overcomes challenging scenes with specular surfaces (PVC floors, water puddles, metals)

Compressive Tracking with Locality Sensitive Histograms Features

Sixian Chan, Xiaolong Zhou, Zhuo Zhang and Shengyong Chen
College of Computer Science and Technology, Zhejiang University of Technology, Hangzhou, China

- The Haar-like features generated from LSH are used to represent the target appearance model.
- A color attributes tracker is employed to predict the target position and to re-build the new discriminant function.
- A novel model updating mechanism is proposed to maintain the stability of features while avoiding noisy.
- A trajectory rectification method is adopted to make the finally estimated location more accurate.

Detecting, Localizing, and Recognizing Trees with a Monocular MAV: Towards Preventing Deforestation

Utsav Shah, Rishabh Khawad, and K Madhava Krishna
RRC, IIIT Hyderabad, India

- Deep learning for tree detection and translation maneuver to obtain dense disparity map.

Combined Image- and World-Space Tracking in Traffic Scenes

Aljoša Ošep and Wolfgang Mehner and Markus Mathias and Bastian Leibe
Visual Computing Institute, RWTH Aachen University, Germany

- Vision-based multi-object tracking framework, suitable for robotics applications.
- We use category-agnostic 3D object proposals for precise localization of detections in 3D space.
- Joint image-space and 3D-space tracking formulation.
- We obtain state-of-the-art results on vision benchmarks, while demonstrating significant improvements in 3D localization.
6-DoF Object Pose from Semantic Keypoints

Georgios Pavlakos¹, Xiaowei Zhou¹, Aaron Chan¹, Konstantinos G. Derpanis², Kostas Daniilidis¹
¹Computer and Information Science, University of Pennsylvania, USA
²Computer Science, Ryerson University, Canada

- We estimate the 6-DoF pose of an object from a single RGB image.
- A Convolutional Network is used to localize 2D semantic keypoints on the image.
- A pose optimization step enforces global consistency of the detected keypoints.
- Our method deals both with instance-based as well as class-based scenarios.

Steps of our approach

Mixtures of Lightweight Deep Convolutional Neural Networks: applied to agricultural robotics

Chris McCool, Tristan Perez and Ben Upcroft
School of Electrical Engineering and Computer Science
Queensland University of Technology, Australia

- Applying deep learning for real-time pixel-level weed classification
- Tradeoff complexity (processing speed) vs accuracy
- Combining multiple compressed models using a mixture of deep convolutional neural networks
- Achieves accuracy > 90% while improving speed by up to an order of magnitude with up to an order of magnitude fewer parameters

Above is AgBot II which can detect and classify weeds in real-time using this approach.
Visual-Based Navigation

Chair Henrik Iskov Christensen, UC San Diego
Co-Chair Timothy Barfoot, University of Toronto

16:25–16:30 TUD4.1

Falling in Line: Visual Route Following on Extreme Terrain for a Tethered Mobile Robot
Patrick McGarey, Max Polzin, Timothy D. Barfoot
University of Toronto Institute for Aerospace Studies, Canada

- When a tethered robot navigates steep, cluttered environments, its supportive tether can become ‘anchored’ on obstacles.
- To avoid entanglement, the robot must retrace its outgoing path to sequentially detach the tether from obstacles (anchors).
- We use the Visual Teach & Repeat (VT&R) algorithm to autonomously retrace a manually taught path on extreme terrain.
- For VT&R to work for tethered robots, we have developed a taut tether controller that (i) allows the robot to drive freely regardless of slope, and (ii) provides motion assistance when wheel traction is reduced.

Our TReX robot autonomously retrace a path on steep, cluttered terrain to avoid entanglement.

16:35–16:40 TUD4.2

Reducing Drift in Visual Odometry by Inferring Sun Direction Using a Bayesian CNN
Valentin Peretroukhin
Institute for Aerospace Studies, University of Toronto, Canada

- We train a Bayesian CNN to infer the 3D direction of the sun from a single RGB image (where the sun is not visible).
- The Bayesian CNN output is a mean and a principled covariance, with median absolute errors of ~12 degrees.
- We use the predictions to improve sliding window stereo VO on the KITTI dataset by up to 42%.

16:45–16:50 TUD4.3

DeepVO: Towards End-to-End Visual Odometry with Recurrent Convolutional Neural Networks
Sen Wang, Ronald Clark, Hongkai Wen and Niki Trigoni
Department of Computer Science, University of Oxford, United Kingdom

- End-to-end monocular Visual Odometry framework is developed to infer poses directly from a sequence of raw RGB images (video).
- It can learn effective feature representation for the Visual Odometry problem through Convolutional Neural Networks.
- Sequential dynamics and relations are modelled implicitly by using Recurrent Neural Networks.
- Experiments based on KITTI dataset verify its good generalization ability in totally new, untrained environments.

16:50–16:55 TUD4.4

Point and line feature-based observer design on SL(3) for Homography estimation and its application to image stabilization
Nicolas Cazy1, Pierre-Brice Wieber1, Paolo Robuffo Giordano2 and François Chaumette1
1INRIA, France, 2CNRS, France

A nonlinear observer for online estimation of a sequence of homographies applicable to image sequences obtained from robotic vehicles equipped with a monocular camera is proposed. The approach taken exploits the underlying Special Linear group SL(3) structure of the set of homographies along with gyrometer measurements and direct point- and line-feature correspondences between images to develop temporal filters for the homography estimate. Theoretical analysis and experimental results are provided to demonstrate the robustness of the proposed algorithm. The experimental results show excellent performance even in the case of very fast camera motion (relative to frame rate), and in presence of severe occlusion, specular reflection, image blur, and light saturation.

17:00–17:05 TUD4.5

Visual Servoing Using Model Predictive Control to Assist Multiple Trajectory Tracking
Nicolas Cazy1, Pierre-Brice Wieber1, Paolo Robuffo Giordano2 and François Chaumette1
1INRIA, France, 2CNRS, France

- Multi-Robot Active Perception scheme based on Model Predictive Control
- Two ground robots needing localization services for following desired trajectories
- One Quadrotor UAV periodically visiting the ground robots and a fixed landmark for keeping the localization covariance as low as possible
- Automatic sequencing of the visiting task by taking into account field of view and actuation constraints
- Simulation results confirm effectiveness of the idea

17:10–17:15 TUD4.6

Visual Triage: A Bag-of-Words Experience Selector for Long-Term Visual Route Following
Kirk MacTavish, Michael Paton, and Timothy D. Barfoot
Institute for Aerospace Studies, University of Toronto, Canada

- Builds on Visual Teach & Repeat 2: a vision-in-the-loop autonomous navigation system with multi-experience localization.
- Selects visually relevant experiences from a large driving history based on what the vehicle is observing right now.
- Enables long-term autonomy by focusing the multi-experience localization on a small but relevant temporal-subset of the map.
Satellite Image-based Localization via Learned Embeddings

Dong-Ki Kim
The Robotics Institute, Carnegie Mellon University, United States
Matthew Walter
Toyota Technological Institute at Chicago, United States

- **Goal:** Estimate a vehicle’s pose by registering ground-level images against a georeferenced satellite view of the environment
- Multi-view neural network learns location-discriminative embeddings matching ground-level images to their corresponding satellite view
- Particle filter maintains pose distribution using the learned embedding as observation model
- **Result:** Localization in environments novel relative to training, despite challenge of significant viewpoint and appearance variation

Direct Visual Odometry in Low Light Using Binary Descriptors

Hatem Alismail, Michael Kaess, Brett Browning, Simon Lucey
The Robotics Institute, Carnegie Mellon University

- Robust visual odometry in poor imaging conditions
- Direct VO with binary descriptors (no keypoints)
- Real-time performance
- Demonstrated in low light underground mines
- Code: https://github.com/halismai/bpvo

Example data
Equalized for visualization
Distributed Robot Systems 2

Chair George J. Pappas, University of Pennsylvania
Co-Chair Jakub Lengiewicz, Institute of Fundamental Technological Research, Polish Academy of Sciences

16:25–16:30 TUD5.1
Rate Impact Analysis in Robotic Systems
Nishant Sharma, Sebastian Elbaum, and Carrick Detweiler
Department of Computer Science and Engineering
University of Nebraska-Lincoln, USA
- Changing the publish rate of a message can impact large portions of robot systems.
- The proposed approach helps developers understand the impact of a data rate change.
- It works by analyzing the code of every component, building a dependency graph, and marking edges as 'dependent' or 'independent'.
- It reduces the impact set identified by comparable approaches by only exploring 'dependent' edges for any given rate change.
- A study on three real ROS systems shows that the approach implementation reduced the impact set by up to 41%.

16:35–16:40 TUD5.3
Distributed comput. of forces in modular-robotic ensembles as part of reconfiguration planning
Pawel Holobut and Jakub Lengiewicz
Institute of Fundamental Technological Research, PAS, Poland
- Distributed algorithm to predict deformation and intermodular forces resulting from a planned reconfiguration step.
- Algorithm can be run by a modular robot itself.
- Elastic frame model of robot was assumed, and Weighted-Jacobi iterative solution scheme was adapted.
- Efficiency of the algorithm was checked for robots with different numbers of modules.

16:45–16:50 TUD5.5
Active Target Tracking with Self-Triggered Communications
Lifeng Zhou and Pratap Tokekar
Electrical and Computer Engineering, Virginia Tech, USA
- We study the problem of reducing communications for multi-robot target tracking.
- The robots need to exchange information to coordinate their actions.
- We propose a self-triggered communication strategy that decides when robots should seek up-to-date information from their neighbors.
- We prove that the self-triggered strategy converges to the optimal configuration.

16:50–16:55 TUD5.6
Multi-Robot Coordination through Dynamic Voronoi Partitioning for Informative Adaptive Sampling in Communication-Constrained Environments
Stephanie Kemna and Gaurav Sukhatme
Computer Science, University of Southern California, USA
John G. Rogers III and Carlos Nieto-Granda
US Army Research Laboratory and IRIM, Georgia Institute of Technology, USA
- A multi-robot coordination approach for adaptive sampling in spatial modeling.
- Our robots repeatedly calculate (decentralized) weighted Voronoi partitions, and runs adaptive sampling within.
- Underwater communication constraints are handled via request-based surfacing events.
- Simulation results show that the addition of the coordination approach results in obtaining higher quality models faster.
Modular Robot using Helical Magnet for Bonding and Transformation

Yosuke Suzuki, Kanazawa Univ., Japan
Masato Yaegashi, UEC, Japan

Yuhei Tsutsui, UEC, Japan
Satoshi Kobayashi, Univ. of Tsukuba, Japan

- A new design of a modular robot using helically magnetized axes is proposed.
- The axes are arranged at all of the edges of the cubic-shaped module.
- The axes contribute to both connection and transformation among the modules.
- Motion experiments are carried out to evaluate the performance.

Resilient Flocking for Mobile Robot Teams

Kelsey Saulnier, David Saldaña, Amanda Prorok, George Pappas, and Vijay Kumar
GRASP Lab, University of Pennsylvania, USA

- Goal: Robots should perform resilient consensus on direction of motion.
- Method: Network resilience is maintained by a hybrid controller which utilizes a lower bound measure and dynamic connectivity management.
- Result: Consensus is guaranteed to converge to a safe heading, even in the presence of non-cooperative communication from team members.

Without resilient flocking a non-cooperative robot controls the team
Combining Self-Supervised Learning and Imitation for Vision-Based Rope Manipulation

Ashvin Nair, Pulkit Agrawal, Dian Chen, Phillip Isola, Pieter Abbeel, Jitendra Malik, Sergey Levine

Learning to Jump in Granular Media: Unifying Optimal Control Synthesis with Gaussian Process-Based Regression

Alex H. Chang and Patricio A. Vela
School of ECE, Georgia Institute of Tech., United States
Christian M. Hubicki and Aaron D. Ames
School of ME, Georgia Institute of Tech., United States
Jeff J. Aguilar and Daniel I. Goldman
School of Physics, Georgia Institute of Tech., United States

Learning to Push by Grasping: Using multiple tasks for effective learning

Lerrel Pinto and Abhinav Gupta
Carnegie Mellon University

Learning Modular Neural Network Policies for Multi-Task and Multi-Robot Transfer

Coline Devin¹, Abhishek Gupta¹, Trevor Darrell¹, Pieter Abbeel¹², Sergey Levine¹
¹EECS, UC Berkeley, USA
²OpenAI
³ICSI

Incorporating Side-Channel Information into Convolutional Neural Networks for Robotic Tasks

Yilun Zhou and Kris Hauser
Department of Electrical & Computer Engineering, Duke University, USA

Learning Feedback Terms for Reactive Planning and Control

Akshara Rai²³*, Giovanni Sutanto¹²*, Stefan Schaal¹² and Franziska Meier¹²
¹USC, USA, ²AMD, MPI-IS, Germany, ³RI, CMU, USA
* contributed equally

Proposed framework for learning feedback terms

Both main-channel image-like information (e.g. camera image) and side-channel information (e.g. GPS location and route) are needed to predict maneuver
An Approach for Imitation Learning on Riemannian Manifolds
Martijn J.A. Zeestraten¹, Ioannis Havoutis²³, João Silvério¹, Sylvain Calinon²¹, Darwin G. Caldwell¹
¹Advanced Robotics Department, Istituto Italiano di Tecnologia, Italy
²Idiap Research Institute, Switzerland
³Oxford Robotics Institute, University of Oxford, United Kingdom

• Generalization of common tools for Imitation Learning to Riemannian Manifolds (Gaussian Conditioning and Product, GMR and TP-GMM).
• Probabilistic regression of robot pose by exploiting variation and coordination.
• Experiment: bi-manual task encoded with a single Riemannian Gaussian.
• The framework is extensible to other types of Riemannian Manifolds.

A Method for Derivation of Robot Task-Frame Control Authority from Repeated Sensory Observations
Luka Peternel, Leonel Rozo, Darwin Caldwell and Arash Ajoudani
HRI² Lab and Learning and Interaction Lab
Dept. of Advanced Robotics, Istituto Italiano di Tecnologia, Genoa, Italy

• We propose a method that enables the robot to autonomously devise an appropriate control strategy from human demonstrations without prior knowledge of the demonstrated task.
• The method is primarily based on analysing patterns and consistency in the observed dataset.
• The dataset is obtained through a demonstration setup that uses motion capture system, force sensor and muscle activity measurement.

Experiments with different tasks: wiping, drilling and sawing.
Computing the Best Grasp in a Discrete Point Set

Yuan Liu
Department of Electrical and Computer Engineering, University of Michigan-Dearborn, USA

- An efficient algorithm for the best grasp among discrete points
- Can be applied with a group of wrench-based grasp quality measures
- Can be applied to any number and type of contacts
- Can be applied on real robot hands

The best grasp of a robot hand at a given pose

Grasp Quality Evaluation and Planning for Objects with Negative Curvature

Shuo Liu and Stefano Carpin
EECS, University of California Merced, USA
Zhe Hu, Hao Zhang, Mingu Kwon, Zhikang Wang, Yi Xu
Dorabot Inc, Shenzhen, China

- Integrate local geometry around each contact with grasp quality evaluation.
- Use adapted friction cone to link negative curvature and grasp quality metrics for force closure grasps
- Generated databases for multiple objects which has negative curvature and tested on real robot (UR5+Dora-Hand).
- Outperformed random grasp quality-wise and on real robot performance

Hierarchical Salient Object Detection for Assisted Grasping

Dominik A. Klein, Boris Illing, Bastian Gaspers, and Dirk Schulz
Cognitive Mobile Systems, Fraunhofer FKIE, Germany
Armin B. Cremers
Bonn-Aachen Int. Center for Information Technology (B-IT), Germany

- Grouping and saliency as same fundamental process, just from two opposing viewpoints
- Saliency calculation adds negligible runtime after hierarchical grouping
- Saliency tree used for object detection defines most salient region and scale for each pixel
- Easy-to-use manipulation system showcases the advantage of a deeply geared segmentation and saliency estimation

A novel actuation configuration of robotic hand and the mechanical implementation via postural synergies

Yuan Liu, Li Jiang, Shaowei Fan*, Dapeng Yang, Jingdong Zhao and Hong Liu
State Key Laboratory of Robotics and System, Harbin Institute of Technology, China

- A human grasp posture collection protocol is proposed to collect the human grasp postures
- A novel module-division actuation configuration of robotic hand based on the built actuation configuration strategies
- Motion of human four finger joints is decomposed to proportion motion, differential motion and chain proportion motion
- Mechanically implemented by pulley, planetary gear differential module and gear transmission chain

A Framework for Optimal Grasp Contact Planning

K. Hang1, J. A. Stork1, N. S. Pollard2 and D. Kragic1
1RPL/CAS, KTH Royal Institute of Technology, Sweden
2Robotics Institute, Carnegie Mellon University, USA

- Formulates optimal fingertip grasping as a path finding problem
- Introduces super-contact grasps and domain specific successor and heuristics functions
- Allows grasp computation by efficient and complete heuristic search algorithms on arbitrary shapes
- Provides sub-optimality bounds for grasp quality

Grasp Stability Assessment Through Unsupervised Feature Learning of Tactile Images

Deen Cockburn, Jean-Philippe Roberge, Thuy-Hong-Loan Le, Alexis Maslyczyk, and Vincent Duchaine
Command and Robotics Laboratory (CoRo), École de Technologie Superieure, Montreal, Canada

- Improving robotic grasping by enabling a robot to distinguish between stable and unstable grasps for a variety of objects.
- Unsupervised feature-learning using pressure images captured by a tactile sensor.
- Learning was made using a database of 540 picks made on 54 everyday objects.
- The sparse coding algorithm in conjunction with an SVM has allow to predict accurately ~79% of the grasp outcome.
Grasping Posture Estimation for a Two-Finger Parallel Gripper with Soft Material Jaws using a Curved Contact Area Friction Model

Jingyi Xu, Nicolas Alt, Zhongyao Zhang, Eckehard Steinbach
Chair of Media Technology, Technical University of Munich, Germany

- We present a friction model for the curved contact area between a deformable object and soft parallel gripper jaws
- We show that the classical planar contact model leads to an overestimation of the friction
- We apply the presented model for grasping posture estimation by simulating the contact for all grasp candidates

Decoupled limbs yield differentiable trajectory outcomes in locomotion and manipulation

Andrew M. Pace and Samuel A. Burden
Electrical Engineering, University of Washington, USA

- Differentiability with respect to initial conditions and away from contacts
- Decoupled limbs assumes inertial decoupling and force decoupling of limbs
- Important consequences for optimization and learning

Curved contact area of the gripper equipped with soft material jaws

Trajectory outcomes for rigid (left) and decoupled limbs (right) robots
Design of an SSVEP-based BCI System with Visual Servo Module for a Service Robot to Execute Multiple Tasks
Shili Sheng, Peipei Song, Lingyue Xie, Zhendong Luo, Wennan Chang, Shurui Jiang and Feng Duan*
Nankai University, China
Haoyong Yu
National University of Singapore, Singapore
Chi Zhu
Maebashi Institute of Technology, Japan
Jeffrey Too Chuan Tan
The University of Tokyo, Japan

End-Effector Airbags to Accelerate Human-Robot Collaboration
Roman Weitschat, Jörn Vogel, Sophie Lantermann, and Hannes Höppner
German Aerospace Center (DLR)

Modeling User Expertise for Choosing Levels of Shared Autonomy
Lauren Milliken and Geoffrey A. Hollinger
School of Mechanical, Industrial and Manufacturing Engineering
Oregon State University, United States

Port-Hamiltonian based control for human-robot team interaction
Martin Angerer, Selma Musić, Sandra Hirche

Making Gait Recognition Robust to Speed Changes using Mutual Subspace Method
Yumi Iwashita¹, Mafune Kakeshita², Hitoshi Sakano³, and Ryo Kurazume²
¹Jet Propulsion Laboratory, California Institute of Technology, USA
²Kyushu University, Japan
³NTT Data Corporation, Japan

A Multiple-Predictor Approach to Human Motion Prediction
Przemyslaw A. Lasota and Julie A. Shah
Department of Aeronautics and Astronautics
MIT, United States

• Single-channel SSVEP
• Visual servo module
• Service robot
• Multiple tasks
• New hardware approach for physical human-robot collaboration in industrial scenarios
• An analysis of peak force and pressure measurements in experiments with a crash-test dummy
• Higher efficiency in industrial tasks while satisfying the requirements of the ISO/TS 15066
• We introduce the Multiple Predictor System (MPS), a method for integrating complementary motion prediction approaches
• MPS trains on available task data and learns to exploit the predictors’ relative strengths
• Implementation combines velocity-based position projection, time series classification, and sequence prediction methods
• Evaluation shows MPS outperforms the individual predictors by 18.5 - 37.3%
Backchannel Opportunity Prediction for Social Robot Listeners

Hae Won Park, Mirko Gelsomini, Jin Joo Lee, Tonghui Zhu, and Cynthia Breazeal
Personal Robots Group, MIT Media Lab, USA

• A social robot listener has been developed that produces listener backchannel feedback while listening to children’s storytelling.
• Backchannel opportunity prediction (BOP) model detects speaker-cue events based on prosodic features in a speech.
• Within- and between-subjects studies revealed that children gaze and speak more to a contingent backchanneling robot. Children perceive the contingent robot as more attentive and more interested in their stories.

Recognizing Social Touch Gestures using Recurrent and Convolutional Neural Networks

Dana Hughes and Nikolaus Correll
Department of Computer Science, University of Colorado Boulder, USA
Alon Krauthammer
The Aerospace Corporation, USA

• Affective touch recognition using pressure-sensitive arrays may be addressed as a robotic material.
• Deep learning models (CNN, CNN-RNN and Autoencoder-RNN) are explored.
• Continuous, real-time classification.
• Memory and computing requirements allow for in-material implementation using small microcontrollers.
Data-Driven Design of Implicit Force Control for Industrial Robots
Matteo Parigi Polverini, Simone Formentin, Le Anh Dao and Paolo Rocco
D.E.I.B., Politecnico di Milano, Milan (Italy)

- A data-driven control approach, based on VRFT algorithm, is applied to the implicit robot force control problem.
- A suitable feedback loop is introduced to make the system entirely depending on the unknown environment transfer function.
- Increased force tracking performance w.r.t. state-of-the-art model-based integral controller, avoiding the risk of instability due to a rough knowledge of the environment model.

Motion Planning with Movement Primitives in Obstacle Environment
Hyoin Kim, Hyeonbeom Lee, Seungwon Choi, Yung-kyun Noh and H. Jin Kim
Aerospace Engineering, Seoul National Univ, South Korea

- On-line motion planning framework
- Combination parametric dynamic movement primitives (PDMPs) and rapidly randomized exploring random trees star (RRT*)
- Extraction of parameter function utilizing Gaussian Process Regression (GPR)

1-Actuator 3-DoF Parts Feeding Using Hybrid Joint Mechanism with Twisted Axis Layout
Ryohei Sakashita and Mitsuhiro Higashimori
Department of Mechanical Engineering
Osaka University, Japan

- A nonprehensile manipulation scheme that controls a 3-DoF motion of a part is proposed.
- The manipulator employs only one actuator and hybrid joint mechanism with twisted axis layout.
- Whirlpool-like trajectories of point masses on the plate are controlled by the sinusoidal input.
- The 3-DoF parts feeding task based on five primitives is demonstrated.
A Learning Based Training and Skill Assessment Platform with Haptic Guidance for Endovascular Catheterization
Wenqiang Chi, Hediyeh Rafii-Tari, Christopher J. Payne, Jindong Liu and Guang-Zhong Yang
Hamlyn Centre, Imperial College London, United Kingdom
Celia Riga and Colin Bicknell
Department of Surgery & Cancer, Imperial College London, United Kingdom

- Train inexperienced operators through informing the correct catheterization maneuvers via tactile feedback
- A haptic interface that can be affixed to existing catheters
- Continuous HMMs for capturing the essential motion patterns from expert demonstrations
- User studies showed significant improvements in the performance of catheterization tasks

Multilateral Surgical Pattern Cutting in 2D Orthotropic Gauze
with Deep Reinforcement Learning Policies for Tensioning
Deep Reinforcement Learning for Tensioning Policies in Pattern Cutting in deformable 2D material with Da Vinci Research Kit.
Evaluation of Robustness to changes in physical parameters and execution on a physical system
Brijen Thananjeyan, Animesh Garg, Sanjay Krishnan, Carolyn Chen, Lauren Miller, Ken Goldberg
UC Berkeley

Improving the Safety of Telerobotic Drilling of the Skull Base via Photoacoustic Sensing of the Carotid Arteries
Sungmin Kim, N. Gandhi, M.A. Lediju Bell and P. Kazanzides
Johns Hopkins University, USA

- Telerobotic system based on research da Vinci System and 3D Slicer for visualization
- Pulsed laser attached to robot instrument (e.g., drill)
- Robot-mounted ultrasound probe receives real-time photoacoustic measurement using the highest intensity of image data to detect carotid arteries
- Define safe region for drilling based on photoacoustic measurement, with ~1 mm accuracy in phantom experiments

Roboscope: A Flexible and Bendable Surgical Robot for Single Portal Minimally Invasive Surgery
Jacob Rosen
Department of Mechanical and Aerospace Engineering, University of California, Los Angeles, USA
Department of Neurosurgery, University of Washington, USA
Sanjay Krishnan
Hamlyn Centre for Robotic Surgery, Imperial College London, UK
Kojiro Tanaka, Ji Ma, and Blake Hannaford
Department of Electrical Engineering, University of Washington, USA

- Roboscope is a surgical robot for minimally invasive surgery designed for skullbase surgery and neurosurgery.
- The system achieved 12 mechanical DOFs.
- The flexible manipulator has two arms which allow surgeons perform complex surgical tasks (The instruments in the picture have 2 mm diameter).
- 3D endoscopic vision is provided by 1.2 mm Scanning Fiber Endoscope.

Three-dimensional Robotic-assisted Endomicroscopy with a Force Adaptive Robotic Arm
Piyamate Wisanuvej, Petros Giataganas, Konrad Leibrandt, Jindong Liu, Michael Hughes, and Guang-Zhong Yang
Hamlyn Centre for Robotic Surgery, Imperial College London, UK

- The work presents the Hamlyn Arm, 6-DoF manipulator equipped with an endomicroscopy tool for real-time "optical biopsy" application.
- Automated force and perpendicular contact control provides optimum image quality on arbitrary 3D tissue surfaces.
- Responsive feedback controllers make the system capable of scanning tissue under motion during in vivo examinations.

Autonomous Suturing Via Surgical Robot: An Algorithm for Optimal Selection of Needle Diameter, Shape, and Path
Sahba Aghajani Pedram, Peter Ferguson, Ji Ma, and Jacob Rosen
Mechanical and Aerospace Engineering Department, UCLA, USA

- Needle shape, diameter, and path directly affect suture depth and tissue trauma in automated suturing.
- Kinematic model of needle-tissue interaction used to formulate needle path planning as nonlinear optimization.
- Off-line simulations were used to evaluate the accuracy and performance of the proposed algorithm.
- The optimization results were confirmed experimentally with the Raven II system.
Orientation Estimation of a Continuum Manipulator in a Phantom Lung

Jake Sganga and David Camarillo
Department of Bioengineering, Stanford University, USA

- Task space control of a continuum manipulator in a phantom lung is presented
- 2 estimation methods are developed to learn the orientation of the manipulator
- The methods are tested on a clinically viable system

The position traces of the distal tip of the robot is shown for each of the control methods.

Effective Manipulation in Confined Spaces of Highly Articulated Robotic Instruments for Single Access Surgery

Konrad Leibrandt, Piyamate Wisanuvej, Gauthier Gras, Jianzhong Shang, Carlo A. Seneci, Petros Giataganas, Valentina Vitiello, Ara Darzi, Guang-Zhong Yang
Hamlyn Centre for Robotic Surgery, Imperial College London, United Kingdom

- Kinematic description of a 9 joint / 7 DoF robot for single access surgery
- Intuitive manipulation close to joint limits allowing dexterous manipulation in confined spaces
- Calibration for backlash compensation to enable precise manipulation
- Experimental evaluation through bench test (peg-transfer, suturing), and ex-vivo test (tumor resection and closure)
### Trajectory Tracking and Balance Control of an Autonomous Bikebot

Pengcheng Wang and Jingang Yi  
Department of Mechanical & Aerospace Engineering, Rutgers University, USA  
Tao Liu  
School of Mechanical Engineering, Zhejiang University, China  
Yizhai Zhang  
School of Astronautics, Northwestern Polytechnical University, China

- Bikebot was developed as a platform for studying physical human-robot interactions.  
- The dynamic model of the bikebot satisfies the external/internal convertible (EIC) properties.  
- We designed and implemented an EIC-based trajectory tracking and balance control.  
- Extensive experiments and comparison with human riding experiments.

### Obstacle Negotiation Learning for a Compliant Wheel-on-Leg Robot

Arthur Bouton and Faïz Ben Amar  
ISIR, UPMC Université Paris 6, France  
Christophe Grand  
ONERA, France

- Use of a compliant design that can measure the external forces applied on legs.  
- Robot advances without any prior knowledge on the ground geometry or obstacle shapes.  
- A Q-learning algorithm maps a discrete set of actions to the continuous state space of the robot.  
- Simulation results prove that the obtained policy allows the robot to successfully cross complex and unknown obstacles.

### Harnessing Steering Singularities In Passive Path Following For Robotic Walkers

Marco Andreetto, Stefano Divan, Daniele Fontanelli, Luigi Palopoli  
University of Trento, Italy

- Assistive robotic walker equipped with front steering wheels.  
- Path following controller completely insensitive to the singularity of zero velocity.  
- Comprehensive experimental tests.

### Path Following Controller for Planar Robots with Articulated, Actuated and Independently Steerable Wheels

Ville Pitkänen, Antti Tikkanen, Anssi Kemppainen and Juha Röning  
Department of Computer Science and Engineering, University Of Oulu, Finland

- Multi-purpose path following controller for planar robots with multiple velocity limited steerable wheels.  
- Smooth path convergence using critically damped virtual springs.  
- Allows relative motion between robot and wheels, yet mathematically simple.  
- Computational cost increases only linearly with number of wheels.

### Multi-modal robot skin

- Self-configuring, self-calibrating  
- Event-driven-system  
- Multi-modal control framework  
- Semantic reasoning system  
- Compliance in non-compliant robots

### Designing for Uniform Mobility Using Holonomicity

John Tighe Costa and Mark Yim  
Mechanical Engineering and Applied Mechanics, University of Pennsylvania, USA

- Holonomicity $H$: the extent to which a vehicle can move equally in all global DOF.  
- Mobility Ellipses can be used to optimize mobility.  
- Holonomic vehicles with low cost offset differential drive and turret have skewed mobility ellipses.
Efficient Path Planning for Mobile Robots with Adjustable Wheel Positions

Freya Fleckenstein, Christian Dornhege and Wolfram Burgard
Department of Computer Science, University of Freiburg, Germany

- Path planning for robots with additional degrees of freedom (adjustable lever arms)
- Planning for full x,y,theta motions and all arm angles (7 DoF)
- Efficient interval-based state space representation

Motion Discontinuity-Robust Controller for Steerable Mobile Robots

By: Mohamed SOROUR
Andrea CHERUBINI
Philippe FRAISSE
Robin PASSAMA