Deutsche Gesellschaft für Robotik

Proceedings

DGR Days 2016

June, 29 – 30, Leipzig

Program Chairs

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Deutsche Gesellschaft für Robotik (DGR)

DGR Days 2016

29.-30. Juni, 2016, Leipzig, Vortragsraum 10, Ebene +2

Congress Center Leipzig
http://www.ccl-leipzig.de/ccl/lage-anfahrt/

Duration of the presentations

Keynotes	30 minutes (25 min talk + 5min Q&A)
Oral presentations	10 minutes (7min talk + 3min Q&A)
Interactive presentations	3min teaser + 30min discussion during following break

Programm

Wednesday, June 29

Time	Session
9:00	Opening Tamim Asfour, Karsten Berns, Jessica Burgner, Oskar von Stryk
9:05	**Keynote: Offroad Robotics** ***Karsten Berns***
9:35	Robust Deep Scene Understanding of Unstructured Environments *Abhinav Valada and Wolfram Burgard*
9:45	Auto-tuning of PID Controllers for Robotic Manipulators Using Particle Swarm Optimization Method *Ahmed Zidan, Jens Kotlarski and Tobias Ortmaier*
9:55	Formal proofing and monitoring of surgical workflows *Luzie Schreiter*
10:05	FPGA-aided, behaviour based control of a robot manipulator *Alexander Köpper and Karsten Berns*
10:08	Autonomous Robotics: Application on Legged and Agricultural Robots *Arne-Christoph Hildebrandt, Daniel Wahrmann, Felix Sygulla, Robert Wittmann, Constantin von Deimling and Daniel Rixen*
10:11	Lidar-Based Localization of an Agricultural Robot in Crop Fields *Alexander Schaefer, Michael Ruhnke and Wolfram Burgard*
10:14	Automatic Channel Selection in Neural Microprobes *Camilo Gordillo and Wolfram Burgard*

10:17	A Bio-Inspired Distributed Balancing Controller for Torque Controlled Humanoid Robots *Lukas Kaul and Tamim Asfour*
10:20	Discussion
10:30	**Coffee Break / Poster Session**
11:00	**Keynote: How to learn and interact ? An integrated perspective on Cognitive Robotics Systems Engineering** ***Jochen Steil***
11:30	New Perception Approaches for Mobile Robots in Low Visibility Environments *Paul Fritsche, Björn Zeise, Patrick Hemme and Bernardo Wagner*
11:40	Learning Task-Priorities based on a Mixture of Torque Controllers *Niels Dehio and Jochen Steil*
11:50	Incremental Bootstrapping of Parametrized Skill Memories *Jeffrey Queißer and Jochen J. Steil*
12:00	Perception of Affordances for Whole-Body Loco-Manipulation *Peter Kaiser, Markus Grotz, Eren Aksoy and Tamim Asfour*
12:10	Analytical Forward and Inverse Kinematics of a Multi-Flexible-Link Robot Arm under Gravity *Freia Irina Mues, Myrel Alsayegh, Jörn Malzahn and Torsten Bertram*
12:20	Discussion
12:30	**Lunch**
13:30	**Keynote: The Story of FRANKA: From Scientific Challenges to the Professional Robot for Everyone** ***Sami Hadddin***
14:00	Indoor Scene Recognition by 3D Object Search for Robot Programming by Demonstration *Pascal Meißner and Rüdiger Dillmann*
14:10	Haptic learning and haptic search for complex shapes *Alexandra Moringen and Helge Ritter*
14:20	Spatial investigation of biologic joints by robotic arms *Constantin von Deimling, Peter Föhr, Andreas Obermeier, Arne-Christoph Hildebrandt, Christoph Schütz, Felix Sygulla, Oliver Hofmann, Daniel Wahrmann, Robert Wittmann, Daniel Rixen and Rainer Burgkart*
14:30	Using Human Demonstrations and Trajectory Optimization for Generalizable Human-like Robot Motions *Dorothea Koert, Guilherme Maeda, Rudolf Lioutikov, Gerhard Neumann and Jan Peters*
14:40	Model Predictive Control for Learning from Demonstration *Myrel Alsayegh, Frank Hoffmann and Torsten Bertram*
14:50	A multimodal capacitive sensor for Grasping and dexterous manipulation *Hosam Alagi*

15:00	Decentralized data-driven control of cooperating sensor-equipped aerial vehicles *Juliane Euler and Oskar von Stryk*
15:03	Combining Gaze Stabilization Reflexes for Humanoid Robots *Markus Grotz, David Sippel and Tamim Asfour*
15:06	Single Camera Based Multiple Pedestrian Tracking for Resource-Limited Hardware Systems *Tanittha Sutjaritvorakul, Songlin Piao and Karsten Berns*
15:09	Whole-Body Sensory Concept for Compliant Mobile Robots *Marina Kollmitz, Andreas Wachaja, Tobias Schubert and Wolfram Burgard*
15:12	System identification of a feed-forward controlled robotic leg to mimic human running gaits *Christian Schumacher, Heiko Schlarb and Andre Seyfarth*
15:15	Discussion
15:30	**Coffee Break / Poster Session**
16:00	**Keynote: Action in Robot Perception** ***Oliver Brock***
16:30	Interactive Perception for Autonomous Robotic Manipulation *Roberto Martín-Martín and Oliver Brock*
16:40	Interlocking Perception-Action Loops at Multiple Time Scales - a System Architecture Proposal for Interactive Perception *Jeannette Bohg*
16:50	Learning Convolutional Filters for Tactile Manipulation *Martin Meier, Robert Haschke and Helge J. Ritter*
17:00	Learning 6D Object Pose Estimation and Tracking *Frank Michel*
17:10	Integrating vision and physical interaction for object segmentation and grasping *David Schiebener*
18:00	**RoboCup 2016 Opening Ceremony**
19:00	**Dinner**

Thursday, June 30

Uhrzeit	Session
9:00	**Keynote: Robot competitions and benchmarking with a benefit for the industry** ***Rainer Bischoff***
9:30	Cognition-Guided Surgery - Context-aware assistance in the operating room of the future *Stefanie Speidel, Sebastian Bodenstedt, Andreas Bihlmaier, Darko Katic, Jessica Hutzl, Martin Wagner, Hannes Kenngott, Beat Müller-Stich, Heinz Wörn and Rüdiger Dillmann*
9:40	Development of Compliant Hyper-redundant Mechanisms for Robotic Catheters and Analysis of Controllability *Pedro Rodriguez Nasdar, Pinar Boyraz, Tobias Ortmaier and Annika Raatz*
9:50	METABot-Magnetic Extensible Tendon Actuated Continuum Robot *Ernar Amanov and Jessica Burgner-Kahrs*
10:00	Real-time 4D Object Modelling for Adaptive Manipulation *Seongyong Koo, Sven Behnke*
10:10	Rapid Motion Planning for Intracerebral Hemorrhage Evacuation using a Tubular Aspiration Robot *Josephine Granna, Yannick Vornehm, Carolin Fellmann and Jessica Burgner-Kahrs*
10:13	Optimal Control of Lifting Motions for Spinal Exoskeleton Design *Paul Manns and Katja Mombaur*
10:16	Robot Learns to Use Tactile Tool Interacting with Unknown Object *Qiang Li, Robert Haschke and Helge Ritter*
10:19	Decentralized Dynamic Data-Driven Monitoring and Estimation of Contaminant Plumes *Tobias Ritter, Stefan Ulbrich and Oskar von Stryk*
10:22	Target Prediction in an Immersive Pick-and-Place Scenario *Dennis Krupke, Frank Steinicke and Jianwei Zhang*
10:25	Probabilistic Camera Localization from Images using Text Spotting *Noha Radwan, Wolfram Burgard, Gian Diego Tipaldi and Luciano Spinello*
10:28	Discussion
10:30	**Coffee Break / Poster Session**
11:00	**Keynote: AI-enabled Robotics --- between cognitive robotics, deep learning, data analytics, and open research** ***Michael Beetz***
11:30	(Inverse) Optimal Control for Matching Higher-Order Moments *Oleg Arenz, Hany Abdulsamad and Gerhard Neumann*
11:40	Motoric activation of persons with early stage dementia with a robotic system *Denis Štogl*

11:50	Proximity Sensors for Safe Human Robot Interaction *Yitao Ding*
12:00	Autonomous Transparent Object Reconstruction *Sven Albrecht and Michael Görner*
12:10	Adaptive Sensor Fusion for RGB-D Object Detection *Oier Andreas Mees, Andreas Eitel and Wolfram Burgard*
12:20	Discussion
12:30	**Lunch**
13:30	**Guided Tour RoboCup 2016**
15:00	**End DGR-Days 2016**

Further information

Webpage DGR Days 2016: https://h2t-projects.webarchiv.kit.edu/Projects/dgr2016/

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Robust Deep Scene Understanding of Unstructured Environments

Abhinav Valada and Wolfram Burgard

***Abstract*— Deep Convolutional Neural Network (DCNN) models have achieved unprecedented performance on various image understanding tasks. However, these models are still susceptible to several disturbances that affect perception in real-world environments including lighting changes, glare and ambient noise. In addition, training of DCNNs require a large amount of annotated data which is difficult to acquire for specialized robotic applications. In this paper, we describe two of our systems that overcome some of these limitations by learning end-to-end hierarchical noise-robust features. First, we give an overview of our multispectral DCNN fusion architecture that enables the network to learn features from multiple modalities and spectra for dense semantic segmentation of forested environments. Secondly, we describe our proprioceptive spatiotemporal model for terrain classification from acoustic vehicle terrain interaction signals. Both of our approaches achieve state-of-the-art performance on extensive real-world data compared to existing techniques. Moreover, our networks perform inference in real-time enabling quick decision making, critical for operating in such environments.**

I. Introduction

Scene understanding is paramount for robots operating in the real-world. Thus far, most of the research has been focused on structured environments where the scene has predictable geometric features and robots are deployed in controlled environments where natural factors such as shadows, glare, snow and ambient noise are not considered. However, for robots operating in unstructured and unknown environments, scene understanding in the presence of such factors is a prerequisite. DCNN approaches have gained tremendous popularity for their unprecedented performance in various applications. However, such approaches are highly dependent on large datasets that, firstly do not exist for such environments and, secondly, techniques to overcome such impediments have not been explored.

In this paper, we tackle this general problem by providing robust solutions to two main mobile robot scene understanding tasks: *Semantic Segmentation* and *Terrain Classification*. We propose a novel DCNN fusion architecture for semantic segmentation using multispectral and multimodal images, namely RGB, Near-InfraRed, and depth data. Our Late-Fused Upconvolution architecture learns complementary features from multiple modalities, thereby achieving robust segmentation in challenging real-world conditions. For terrain classification, we propose a deep spatiotemporal recurrent model that uses only vehicle-terrain interaction sounds. Our model utilizes our proposed noise-aware training scheme to learn robust features that effectively generalize to high ambient noise environments.

All authors are with the Department of Computer Science, University of Freiburg, Germany. This work has been partly supported by the European Commission under the grant numbers ERC-AGPE7-267686-LifeNav and FP7-610603-EUROPA2. Demo is publicly available at `http://deepscene.cs.uni-freiburg.de` and `http://deepterrain.cs.uni-freiburg.de`.

II. Related Work

Although there are numerous traditional learning approaches relating to recognition from RGB-D data, there are limited amount of DCNN approaches that have explored the use of multiple modalities or spectra. Schwarz *et al.* [1] use a pre-trained two stream ImageNet network for object recognition from RGB-D images, while, Bo *et al.* [2] proposed an approach called hierarchical matching pursuit, which uses hierarchical spare coding to learn features from multimodal data. These approaches are limited to learning combined features from the early stage, and thereby are not suitable for learning complementary features as well as combined discriminative features after the fusion.

Terrain classification approaches primarily use RGB images or lidars and are therefore highly affected by visual appearance changes due to seasons and weather conditions. Terrain classification using acoustics has previously been explored but has been limited to three terrain classes and experiments in the presence of ambient noise has not been considered [3]. Our approach classifies nine different indoor and outdoor terrains, and in addition considers ambient noise disturbances.

III. Technical Approach

Our segmentation architecture is composed of two streams, each consisting of a contraction and expansion component that first individually learn to segment a specific modality or spectra, which is then followed by an element-wise summation of the feature maps and a series of convolution, pooling and upconvolution layers. Our fused result outperforms segmentation using only RGB data and other state-of-the-art, end-to-end segmentation networks.

Our acoustics-based terrain classification model consists of a new DCNN architecture that learns deep spatial features, complemented with Long-Short Term Memory units and a new statistical pooling strategy that enables the network to learn complex temporal dynamics in the signal. Our noise-aware training scheme injects random ambient noise while training thereby achieving improved robustness in real-world environments. Through extensive experiments we demonstrate that our network outperforms classification using traditional audio features, achieving state-of-the-art performance.

References

[1] M. Schwarz, H. Schulz, and S. Behnke, "Rgb-d object recognition and pose estimation based on pre-trained convolutional neural network features," in *ICRA*, 2015.

[2] L. Bo, X. Ren, and D. Fox, "Unsupervised Feature Learning for RGB-D Based Object Recognition," in *ISER*, June 2012.

[3] J. Libby and A. T. Stentz, "Using sound to classify vehicle-terrain interactions in outdoor environments," in *ICRA*, May 2012.

Auto-Tuning of PID Controllers for Robotic Manipulators using Particle Swarm Optimization

Ahmed Zidan[1], Jens Kotlarski[2], and Tobias Ortmaier[3]

***Abstract*— A practical approach for the auto-tuning of PID controllers for robotic manipulators is proposed. The approach uses the particle swarm optimization in order to find optimal gain values achieving the best tracking of a predefined trajectory. For this purpose, the integral of the absolute error is used as a cost function for the optimization algorithm. Additionally, two constraints are defined: a maximum joint torque and a maximum position error.**

I. Motivation

PID control schemes provide simple and effective solutions for most applications of control engineering. However, the effectiveness of PID controllers significantly depends on the tuning of the controller gains.

Robotic manipulators are highly non linear, highly coupled, Multi-Input Multi-Output (MIMO) dynamic systems. Using a PID controller to control robotic manipulators can be a desired choice because of its simplicity and effectiveness. However, conventional tuning methods of the gains depending on manual or experimental approaches do not necessarily give satisfactory results for such complex systems [1].

II. Related Work

Recently, thanks to the rapid increase of computing power, auto-tuning methods based on optimization techniques has been applied to non linear systems in order to obtain an enhanced performance with respect to predefined fitness functions. In the field of robotic manipulators, a number of optimization methods (e. g. Genetic Algorithms (GA) [2], Particle Swarm Optimization (PSO) [3]) has been used to automatically tune PID controllers of robots. Also, comparative studies between different techniques have been done in [4] and [5] in order to find the most effective tuning method. The known and previously mentioned research focusses on analyzing and developing the optimization algorithm itself. For this purpose, the validation of the proposed methods has only been tested using simple simulations. However, from a practical point of view, attention needs to be diverted to the tuning problem itself, i. e. necessary constraints guaranteeing a safe movement of the robot. Otherwise, due to stability problems, searching for optimal gain values is not practicable.

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III. Proposed Approach and Contribution

The proposed approach aims at finding a general auto-tuning method for PID controllers of robotic manipulators. The suggested method uses the particle swarm optimization technique. The main contribution of this research is to propose a practical implementation of the PSO for robotic manipulators. In this context, a searching procedure for optimal gain values is introduced. This procedure starts with defining the PSO parameters (e. g. swarm size, maximal iteration, number of swarms, ...). Strategies for choosing those parameters are suggested in [6]. After that, the motion constraints for every joint (maximal motor torque and maximal position error) are defined based on the actuators specifications and the desired accuracy of the performed task. The objective function is chosen to be the integral of the absolute position error IAE:

$$IAE = \int \boldsymbol{e}(t)\mathrm{d}t = \int (\boldsymbol{q}_\mathrm{d}(t) - \boldsymbol{q}(t))\mathrm{d}t\,.$$

Hence, the optimization problem including the proposed constraints results to:

$$\hat{K} = (\hat{\boldsymbol{k}}_\mathrm{P}, \hat{\boldsymbol{k}}_\mathrm{D}, \hat{\boldsymbol{k}}_\mathrm{I}) = \arg\min_K IAE,$$
$$|\boldsymbol{\tau}| \leq \boldsymbol{\tau}_\mathrm{max}, |\boldsymbol{e}| \leq \boldsymbol{e}_\mathrm{max}$$

At the beginning, the algorithm assigns random initial positions to the swarm particles and calculates their objective values. This is done by executing the corresponding motions for every set of gain values. Then, the search continues until one of the termination conditions is achieved. If one of the constraints is violated, the movement is terminated immediately and new gain values are assigned to the corresponding particles.

References

[1] M. A. Johnson and M. H. Moradi, *PID control*. Springer, 2005.

[2] R. Sharma, K. Rana, and V. Kumar, "Statistical analysis of ga based pid controller optimization for robotic manipulator," 2014, pp. 713–718.

[3] N. Kapoor and J. Ohri, "Improved pso tuned classical controllers (pid and smc) for robotic manipulator," *International Journal of Modern Education and Computer Science (IJMECS)*, vol. 7, 2015.

[4] P. Ouyang and V. Pano, "Comparative study of de, pso and ga for position domain pid controller tuning," *Algorithms*, vol. 8, 2015.

[5] D. Kwok and F. Sheng, "Genetic algorithm and simulated annealing for optimal robot arm pid control," in *Evolutionary Computation, 1994. IEEE World Congress on Computational Intelligence*, 1994, pp. 707–713.

[6] A. Rezaee Jordehi and J. Jasni, "Parameter selection in particle swarm optimisation: a survey," *Journal of Experimental & Theoretical Artificial Intelligence*, vol. 25, pp. 527–542, 2013.

Formal proofing and monitoring of surgical workflows

Luzie Schreiter

***Abstract*— This work addresses the challenges of design workflows in a safe manner for surgical robotic systems and to monitor the workflow online. The overall goal is to ensure that the patient and the operating room staff are safe. The definition of the workflow is based on expert knowledge in an intuitive workflow editor for OWL based semantic networks. A discrete abstraction and task specification using computation tree logic (CTL) is used to automatically check whether this workflow meets a given specification. To follow the predefined and consistency workflow and to deliver a suitable assistance for the surgeon at a proper time, machine learning methods are used. The trained transition models are integrated in the surgical setup and evaluated.**

I. Motivation and Problem Definition

In contemporary medicine, the use of assistance functions for diagnosis and surgical interventions is an evolving area. These functions can help to master medical challenges like enhancement of outcome or the preservation of a high level of satisfaction for employees as well as patients. To monitor a surgical intervention a proper surgical plan has to be defined. In this approach the safe definition of a surgical workflow in a content related as well as formal consistent way and the monitoring of the surgical workflow in realtime is focused.

II. Related Work

Current approaches based on surgical workflows focussing to recognise the currently active phase of the workflow [1], [2], [3] and to analyse the progress of the surgery [4]. Nevertheless, methodical faults, like a not conclusive plan in itself, are not taken under consideration. On the other hand current approaches [5], [6], [7] are focussing on the formalization and verification of very isolated aspects during a robot-aided surgical scenario. Brining this two aspects together is the challenge of this work.

III. Own Approach and Contribution

The approach is split into two phases: *pre-* and *intra-operative*. Fig. 1 presents an overview. First the surgical workflow will be defined using a editor. The editor extracts the logic of possible task sequences out of a semantic network [8]. To eliminate failure behaviour the workflow will investigate by using model checking which leads to a formal correct workflow. This workflow will serve as basis for the real intervention, e.g. as control concept for the robot-aided system. Moreover the transition models, which will identify a state change during the intervention, will be trained using machine learning techniques. The transition models will be integrated into surgical setup. A 3D camera supervision system [9] delivers the input data to the transition models. During the surgery a situation detection will take place [10], [11]. This is mandatory to monitor the system, to identify derivation of the plan which could led to safety critical situations or to deploy a suitable assistant to the surgeon.

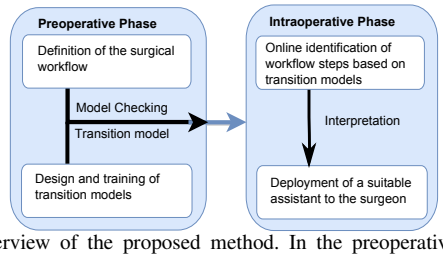

Fig. 1: Overview of the proposed method. In the preoperative phase the surgical workflow will be defined and verified as well as the transition models are trained. During the intra operative phase the surgical workflow will be monitored and a deployment of a suitable assistant takes place.

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References

[1] N. Padoy, T. Blum, S. Ahmadi, H. Feussner, M.Berger, and N. Navab, "Statistical modeling and recognition of surgical workflow," *Medical Image Analysis*, vol. 16, no. 3, pp. 632 – 641, 2012, computer Assisted Interventions.

[2] T. Blum, H. Feußner, and N. Navab, "Modeling and segmentation of surgical workflow from laparoscopic video," in *Medical Image Computing and Computer-Assisted Intervention*, ser. LNCS 6363. Springer, 2010.

[3] F. Lalys, D. Bouget, L. Riffaud, and P. Jannin, "Automatic knowledge-based recognition of low-level tasks in ophthalmological procedures," *Int. J. of Computer Assisted Radiology and Surgery*, vol. 8, no. 1, pp. 39–49, 2013.

[4] T. Neumuth, P. Liebmann, P. Wiedemann, and J. Meixensberger, "Surgical workflow management schemata for cataract procedures," *Methods of Information in Medicine*, vol. 51, no. 4, pp. 371–382, 2012.

[5] R. Muradore, D. Bresolin, L. Geretti, P. Fiorini, and T. Villa, "Robotic surgery: Formal verification and plans," *Robotics Automation Magazine, IEEE*, vol. 18, no. 3, pp. 24 –32, sept. 2011.

[6] L. Benvenuti, D. Bresolin, A. Casagrande, P. Collins, A. Ferrari, E. Mazzi, A. Sangiovanni-Vincentelli, and T. Villa, "Reachability computation for hybrid systems with Ariadne," *Proc., 17th IFAC World Cong.*, 2008.

[7] Y. Kouskoulas, D. Renshaw, A. Platzer, and P. Kazanzides, "Certifying the safe design of a virtual fixture control algorithm for a surgical robot," in *Proc., 16th Int. Conf. on Hybrid Systems: Computation and Control (HSCC 2013)*. ACM, 2013.

[8] S. Dürr, A. Huck, L. Schreiter, T. Beyl, J. Giehl, M. Schwarz, J. Raczkowsky, and H. Wörn, "Intuitive workflow editor for OWL based semantic networks in medical environment," in *International Journal of Computer Assisted Radiology and Surgery*, 2016, p. Forthcoming.

[9] T. Beyl, L. Schreiter, P. Nicolai, J. Raczkowsky, and H. Wörn, "3D Perception Technologies for Surgical Operating Theatres," *NextMed/MMVR22*, p. Forthcoming, 2016.

[10] L. Schreiter, E. Berghoeffer, T. Beyl, L. Senger, J. Raczkowsky, and H. Woern, "Probabilistic situation detection for human-robot interaction in an op lab environment," *Curac*, pp. 99–104, 2015.

[11] L. Schreiter, P. Philipp, J. Giehl, Y. Fischer, J. Raczkowsky, M. Schwarz, J. Beyerer, and H. Wörn, "Situation Detection for an Interactive Assistance in Surgical Interventions Based on Random Forests," in *International Journal of Computer Assisted Radiology and Surgery*, 2016, p. Forthcoming.

FPGA-aided, behaviour based control of a robot manipulator

Alexander Köpper[1] and Karsten Berns[1]

***Abstract*— For many robotic tasks, fast and robust reaction on stimuli from outside is a main objective. Behaviour-based systems have proven to satisfy this need. However, since they are usually implemented on processor-based systems, the full potential of their parallel structure can not be exploited. Using FPGAs especially on the low and time-critical layer of the system can overcome this problems but also yields some challenges for a reasonable implementation. In our work, we aim at utilizing the fully parallel structure of this FPGA-based architecture to improve the performance of a robotic system, based on our behaviour-based architecture iB2C.**

I. Motivation and Problem Definition

Robotic tasks like moving through unknown, rough terrain, walking or even grasping require the ability to react on changes in the environment robust as well as fast. This is often limited by high round trip times, caused by extensive calculations on a processing unit. Behaviour-based architectures like "iB2C", which was developed at our Lab, aim on overcoming this by avoiding the mathematical formalisation partially. iB2C is composed of many parallel behaviours, which have a defined common interface, but are not limited from their inner structure. Through the interaction of these behaviours, an overall behaviour of the system emerges. Unfortunately, the current implementation for processor-based systems cannot exploit the full potential of this architecture. The problem is, that due to the serial execution structure of the middle-ware, the operating system and the processor itself, the advantages of the parallel structure of the architecture decrease with the round-trip time. This problem becomes visible especially when moving from a simulated environment to the real world. Additionally, these delays may lead to erroneous results due to e. g. outdated values or false scheduling. A truly parallel implementation is not possible on a standard processor and also multi-core units or GPUs can solve this only to a certain point. Implementing the system on FPGAs seems to be the natural solution. However, many constructs used for common implementations, like complex algebraic functions , are difficult to implement on them. For this, development tools and suitable algorithms have to be identified and compared.

II. Related Work

Besides the classical control approaches, there have been several works on behaviour-based arm control like [1] or [2], who achieve good performance with their algorithms. However, their approaches are all implemented on processor-based architectures. On the other hand, there are several works, which focus more on the utilization of special algorithms, like CORDIC [3] to solve the kinematics, like [4], [5] or [6]. These make use of hardware-based platforms like FPGAs or ASICs, but only use the algorithmic cores as co-processing units to a central processor. Although there are implementations of behaviour-based control algorithms for robots on FPGAs, like [7], there seems to be no newer research focussing on the behaviour-based system itself.

III. Own Approach and Contribution

In our approach, we try to utilize the parallel structure of implementations on an FPGA to implement time-critial and safety-relevant parts of the system. As a proof of concept, we aim at controlling a 6-DOF robot arm based on a mobile platform. To realise this in a behaviour-based architecture, several problems have to be addressed: One one hand, our behaviours are not limited in their inner structure, which may become a problem, when sophisticated algebraic functions are used, since this means a high effort on an FPGA. On the other hand, many rules and limits of iB2C, which were given by the processor-based realization, have to be redefined. Also, since not all processes in such a system are fully parallelisable, the correct timing of the system is a big issue, since there is no inherent scheduler or arbiter to manage this.

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References

[1] S. Pluzhnikov, D. Schmidt, J. Hirth, and K. Berns, "Behavior-based arm control for an autonomous bucket excavator," in *Proceedings of the 2nd Commercial Vehicle Technology Symposium (CVT 2012)*, K. Berns, C. Schindler, K. Dreßler, B. Jörg, R. Kalmar, and G. Zolynski, Eds. Kaiserslautern, Germany: Shaker Verlag, March 13-15 2012, pp. 251–261.

[2] Z. Wasik and A. Safiotti, "A fuzzy behavior-based control system for manipulation," in *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, vol. 2, IEEE. Lausanne, Switzerland: IEEE, September 30 - October 4 2002, pp. 1596–1601.

[3] J. E. Volder, "The cordic trigonometric computing techniqu," *IRE Transactions on Electronic Computers*, vol. EC-8, no. 3, pp. 330–334, September 1959.

[4] Z. Yili, S. Hanxu, J. Qingxuan, and S. Guozhen, "Kinematics control for a 6-dof space manipulator based on arm processor and fpga co-processor," in *Proceedings of the IEEE International Conference on Industrial informatics (IDIN2008)*, IEEE. Daejeon, Korea: IEEE, July 13-16 2008.

[5] I. D. Walker and J. R. Cavallaro, "Parallel vlsi architectures for real-time kinematics of redundant robots," *Journal of Intelligent and Robotic Systems*, vol. 9, no. 1, pp. 25–43, February 1994.

[6] U. D. Meshram and R. R. Harkare, "Fpga based five axis robot arm controller," *International Journal of Electronics Engineering*, vol. 2, no. 1, pp. 209–211, June 2010.

[7] A. Kongmunvattana and P. Chongstitvatana, "A fpga-based behavioral control system for a mobile robot," in *IEEE Asia-Pacific Conference on Circuits and Systems. Microelectronics and Integrating Systems.*, IEEE. Chiangmai, China: IEEE, November 24-27 1998, pp. 759–762.

Autonomous Robotics: Application on Legged and Agricultural Robots

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Constantin v. Deimling[2] and Daniel Rixen[1]

***Abstract*— Although there have been remarkable advances in the technology of biped robots, large disturbances and motion generation in complex environments are still limiting autonomous walking. In this contribution we present our approach to improve bipedal walking in unknown environments. The objective is to give other researchers from different robotic domains an overview of our research platform *Lola* and our walking controller. We focus not only on results, but also on open questions. Further, we discuss the transfer of methods from and to other domains with the example of an agricultural robot.**

Keywords: Autonomous Robotics, Legged Robots, Agricultural Robots

I. Motivation

The 2013 earthquake in Japan and the following partial meltdown in the Fukushima Dai-Ichi nuclear power plant have greatly increased interest in autonomous machines capable of operating in inaccessible areas using tools created for humans. Such disaster recovery tasks satisfy the "three Ds" of robotics, they are dirty, dangerous and dull. Human-like machines are a promising approach to such tasks, as their structure is adapted to the tools and environment engineered for humans. In our research we focus on some of the shortcomings in the current state of the art of bipedal walking that have made practical applications of bipedal robots elusive. Specifically, we are addressing (1) real-time motion generation based on on-board environment perception that handles dynamic balance, 3D-collision avoidance and local footstep planning, as well as (2) robust walking control based on predictive control to stabilize the robot during large disturbances.

II. Related Projects

A few years ago, the IEEE RAS Technical Committee *Model-Based Optimization for Robotics* [1] was founded. Related to this activity is the EU-founded project *Koroibot*. The focus of this project lies on the development of new concepts for the walking-pattern generation of humanoids. The idea of the project is to transfer human strategies for motion generation via transfer rules to the machines. A great resonance achieved the recently finished *DARPA Robotics Challenge*. It is an international robotics challenge which was founded by the *Defense Advanced Research Projects Agency (DARPA)*. The participating teams had to solve tasks, which were related to possible rescue operations. From a research point of view, the focus was more on the development of methods for semi-teleoperated navigation, on the manipulation and on the development of vision systems than on the development of walking controllers [2], [3]. Recently, the *Google* owned companies *Schaft* and *Boston Dynamics* published great videos showing their biped robots navigating outdoors. Unfortunately, beside videos, no further informations are published.

III. Own Approach and Contribution

In our contribution we present the results of our current project *Walking in Uneven Terrain*[1]. We give an overview of the walking controller of our biped robot *Lola*. On the basis of the application of *Walking in Uneven Terrain*, we give an example of how a robotic system can still be reactive to disturbances or dynamically changing environments while solving complicated motion generation problems. This is a basic problem of a wide range of applications for autonomous robotics from flexible production to navigating in real environments. The objective of our contribution is not to show new algorithms but to give other participants, also from other robotic domains, an insight of the walking controller of a humanoid robot. To further open our results to researchers from other robotic fields, we discuss the transfer of algorithms at the application of an agricultural robot. That way, we hope to find, on the one hand, new possible application areas for our algorithms. On the other hand, we try to give other researchers an interesting application on a real humanoid robot for their methods.

References

[1] K. Mombaur, A. Kheddar, K. Harada, T. Buschmann, and C. Atkeson, "Model-based optimization for robotics," *Robotics Automation Magazine, IEEE*, vol. 21, no. 3, pp. 24–161, 2014.

[2] R. Deits and R. Tedrake, "Footstep planning on uneven terrain with mixed-integer convex optimization," in *IEEE-RAS International Conference on Humanoid Robots*. IEEE, 2014.

[3] A. Stumpf, S. Kohlbrecher, D. C. Conner, and O. V. Stryk, "Supervised Footstep Planning for Humanoid Robots in Rough Terrain Tasks using a Black Box Walking Controller," in *IEEE-RAS International Conference on Humanoid Robots*. IEEE, 2014.

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Lidar-Based Localization of an Agricultural Robot in Crop Fields

Alexander Schaefer, Michael Ruhnke, and Wolfram Burgard

***Abstract*— Conventionally, robots for precision agriculture rely on expensive sensor equipment like Real Time Kinematic (RTK) satellite navigation to localize themselves in crop fields. In the following, we present a novel localization concept that, given a map of the field, requires only odometry and 3D Lidar sensing to produce a pose estimate accurate within 5 cm.**

I. Motivation and Problem Definition

In precision agriculture, plants are individually monitored and treated to minimize cost and environmental pollution, while at the same time maximizing yield. Autonomous ground robots are ideally suited to efficiently achieve this goal: They can continuously drive along the field rows, recognize weeds, mechanically remove them, and apply fertilizer to crops whose infra-red images indicate the need for nutrients.

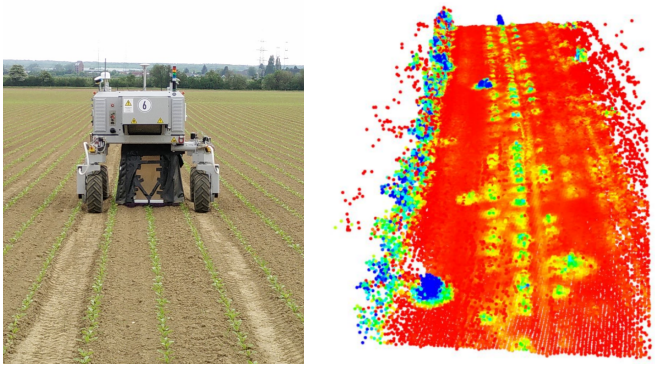
Navigating the rows of a densely-sown field requires high localization accuracy. Typically, the robot runs over and damages plants when it deviates a mere 10 cm from the lane (see fig. 1a). Thus, we aim at estimating the robot pose with a resolution of approximately 5 cm.

II. Related Work

Robot localization has been a very active field of robotics research for decades. For structured environments, there exists a multitude of high-accuracy localization approaches, often relying on 3D point clouds provided by Lidar scanners [1]. For unstructured environments like fields, however, conventional Lidar-based localization approaches fail due to the lack of reference objects. Thus, most agricultural robots rely on expensive RTK satellite navigation systems, which output the robot position with centimeter accuracy [2], or on artificial landmarks positioned in the field [3]. But RTK localization, apart from being very expensive, does not work reliably under tree canopies at forest borders; artificial landmarks require time and effort for setup and for their tedious calibration procedure.

III. Our Approach and Contribution

In order to have an inexpensive out-of-the-box system, our approach localizes the robot accurately by using only odometry information and 3D point clouds provided by the Lidar sensors. Standard Monte Carlo localization would take the odometry as motion estimate and the point cloud as sensor measurement. The latter would in turn be compared point-to-point to an existing map to compute the weight of every pose hypothesis. As stated above, this technique fails in environments that provide as little structure as a field of crops (see fig. 1a). Therefore, we combine the point cloud-based localizer with a feature-based one.



(a) Our test platform BoniRob on a sugar beet field

(b) Local map built from BoniRob's Lidar scans

Fig. 1: Building a local map from 3D Lidar point clouds

Our method works as follows: In a first step, we bundle a small number of Lidar scans to create dense local maps (see fig. 1b). These maps are then segmented to separate the ground from the individual plants. The subsequent step uses the point clouds of the extracted plants to estimate the positions of their stems. By comparing these coordinates with the stem coordinates stored in the map using a custom data association technique, we obtain a precise robot pose estimate with respect to the map.

Our approach is cost-effective and requires a short setup time. Moreover, as the stem coordinates are time-invariant, it is robust against the dynamics of the environment, for example growing plants and changing weather conditions.

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References

[1] S. Thrun, W. Burgard, and D. Fox, *Probabilistic Robotics (Intelligent Robotics and Autonomous Agents)*. The MIT Press, 2005.

[2] M. Nørremark, H. W. Griepentrog, J. Nielsen, and H. T. Søgaard, "The development and assessment of the accuracy of an autonomous gps-based system for intra-row mechanical weed control in row crops," *Biosystems Engineering*, vol. 101, no. 4, pp. 396–410, 2008.

[3] T. Hague, J. Marchant, and N. Tillett, "Ground based sensing systems for autonomous agricultural vehicles," *Computers and Electronics in Agriculture*, vol. 25, no. 12, pp. 11 – 28, 2000. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0168169999000538

Automatic Channel Selection in Neural Microprobes

Camilo Gordillo and Wolfram Burgard

***Abstract*— State-of-the-art neural microprobes contain hundreds of electrodes within a single shaft. Due to hardware and wiring restrictions, it is usually only possible to measure a small subset of the available electrodes simultaneously. The identification of the best channels is usually done offline either manually or automatically. However, a fixed selection for long-term observation does not allow the system to react to changes and may therefore lead to the loss of important information. In our research we approach this problem as a combinatorial multi-armed bandit task. Our system is able to adapt its selection policies to changing environments and to identify the electrodes with the largest amount of non-redundant information online. To the best of our knowledge, this is the first online approach proposed in this context.**

I. Motivation and Problem Definition

There is a growing interest in the development of high-resolution neural microprobes capable of recording the activity of single neurons. Current microprobes may contain hundreds of electrodes within a single shaft; however, due to the size and hardware constraints emerging when developing fully-implantable devices, it is usually only possible to record a small subset of electrodes simultaneously. Typically, an experimenter would scan the probe looking for the most informative channels for long-term recording. As the number of electrodes increases, however, the manual selection becomes impracticable and inefficient. Besides, having a fixed selection does not allow the system to react to changes in the neural activity and may lead to the loss of important information. Our research focuses on the development of intelligent systems for autonomously learning and updating electrode selection policies during long-term observations.

II. Related Work

There are few studies in the area of automatic channel selection for neural microprobes and, to the best of our knowledge, ours is the first online approach proposed in this area. Seidl et al. [1] propose a semi-supervised approach which computes the signal-to-noise ratio (SNR) of the recorded electrodes in order to assist the experimenter in the selection process. Similarly, Van Dijck et al. [2] present an automatic approach which employs the SNR as a quality measure for each electrode, and additionally penalizes each channel according to its similarity with respect to the already selected ones. Applying the penalization avoids the recording of redundant information and leads to a better distribution of the recording channels in a simulated neuronal model.

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III. Own Approach and Contribution

We formulate the process of selecting the best subset of electrodes as a combinatorial multi-armed bandit problem in which the agent repeatedly chooses between different possible selections and obtains a reward. The goal of the agent is to maximize the cumulative reward by identifying optimal policies. The rewards are computed based on the amount of non-redundant information extracted from the signals. We evaluate the algorithms performance on a data set of neural activity recorded in vivo from the neocortex of Wistar rats [3]. Experiments are performed by introducing artificial changes in the data sets. The performance is evaluated with respect to an optimal selection policy which always achieves the best possible performance. Figure 1 shows how our approach converges to a near-optimal selection in less than one minute and, contrary to a fixed long-term selection, can react to changes and adapt its selection strategies to maximize the amount of received information.

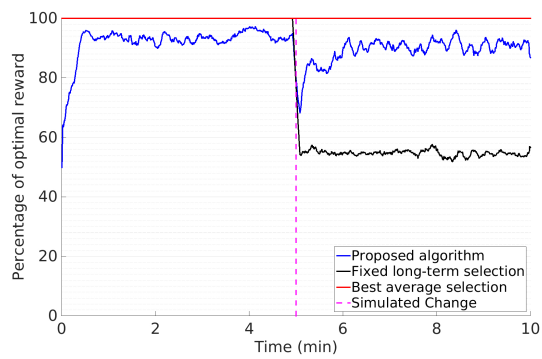

Fig. 1: Performance when selecting 8 out of 72 available electrodes. The damage of half of the optimal electrodes is simulated at minute 5.

References

[1] K. Seidl, T. Torfs, P. De Maziere, G. van Dijck, R. Csercsa, B. Dombovari, Y. Nurcahyo, H. Ramirez, M. van Hulle, G. Orban, O. Paul, I. Ulbert, H. Neves, and P. Ruther, "Control and Data Acquisition Software for High-Density CMOS-Based Microprobe Arrays Implementing Electronic Depth Control," *Biomedizinische Technik*, vol. 55, pp. 183–191, 2010.

[2] G. van Dijck, K. Seidl, O. Paul, P. Ruther, M. van Hulle, and R. Maex, "Enhancing the Yield of High-Density Electrode Arrays Through Automated Electrode Selection," *International Journal of Neural Systems*, vol. 22, no. 01, pp. 1–19, 2012.

[3] K. Seidl, M. Schwaerzle, I. Ulbert, H. Neves, O. Paul, and P. Ruther, "CMOS-Based High-Density Silicon Microprobe Arrays for Electronic Depth Control in Intracortial Neural Recording - Characterization and Application," *Journal of Microelectromechanical Systems*, vol. 21, pp. 1426–1435, 2012.

A Bio-Inspired Distributed Balancing Controller for Torque Controlled Humanoid Robots

Lukas Kaul and Tamim Asfour[1]

***Abstract*— We present a torque-control based distributed controller for humaonoid balancing and push-recovery, consisting of independent joint-level controllers in each actuated joint of the robot. Each individual controller has three objectives: gravity compensation, position control and balancing. The torques computed to fulfill each objective are summed up and form the joint torque that is applied to the respective joint. The concept draws its inspiration from recent results in neurological research and aims at answering the question of how to design an efficient, versatile and robust balance control that produces motions similar to those of humans. The controller was implemented for a simple robot model with three actuated joints and tested in a physics simulation. The results show the ability to successfully recover balance when falling from small heights or being pushed from either the front or the back.**

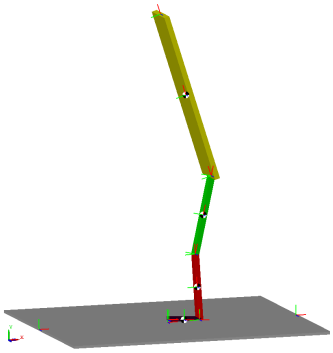

Fig. 1. Simulation model with three actuated joints used to evaluate the proposed balance controller for balancing in the sagittal plane.

I. Motivation and Problem Definition

Balancing robustly and to reacting efficiently to unpredicted balance disturbances is one of the most crucial abilities for bipedal humanoid robots. Yet it is still not known how a balance controller needs to be designed that achieves the levels of robustness, versatility, efficiency and grace that humans exhibit in balancing. Recent research results in experimental neurology suggest that there might exist a distributed control architecture in humans, consisting of joint-level controllers that are independent from each other to a certain degree. The aim of this work is to translate this idea into a control scheme that can be applied to a humanoid robot and to validate the feasibility of the approach in a physics simulation.

II. Related Work

An overview over conventional push-recovery strategies can be found in [1]. The fundamental work describing the *Disturbance Estimation and Rejection (DEC)* concept that inspires the proposed control mechanism can be found in [2]. In [3], Lippi et al. further elaborate on the ideas and findings presented in [2]. Ott et al. compare DEC and model based approaches in [4].

III. Own Approach and Contribution

The here presented approach implements a simple instantiation of the DEC concept described in [2]. The only input to the control system is the position of the Center of Pressure (CoP) in the supporting foot, estimated from discrete force sensors in the foot sole. A torque that is proportional to the deviation of the CoP from the center of the support polygon is applied in each of the joints. These torques cause whole body motions that balance the body under the influence of disturbances. In addition to the so generated balancing torques, proportional-derivative (PD) controllers at joint level generate joint torques that let the joint track a trajectory and the robot maintain its posture. Thirdly, to remove effects caused by gravity, torques generated at each joint by a model-based gravity compensation algorithm are added to the aforementioned components. A simple model of the proposed controller is implemented in a physics simulator and experiments with pushes applied from the back and the front while simultaneously tracking joint trajectories demonstrate the feasibility of the approach. Further work will include a more rigorous evaluation and the application of machine learning techniques to identify optimal control parameters.

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References

[1] B. Stephens, "Humanoid push recovery," *2007 7th IEEE-RAS International Conference on Humanoid Robots*, pp. 589–595, Nov. 2007.

[2] T. Mergner, "A neurological view on reactive human stance control," *Annual Reviews in Control*, pp. 177–198, 2010.

[3] V. Lippi, T. Mergner, and G. Hettich, "A Bio-inspired Modular System for Humanoid Posture Control," *International Conference on Intelligent Robots and Systems (IROS)*, 2013.

[4] C. Ott, B. Henze, G. Hettich, T. N. Seyde, M. A. Roa, V. Lippi, and T. Mergner, "Good posture, good balance: Comparison of bioinspired and model-based approaches for posture control of humanoid robots," *IEEE Robotics Automation Magazine*, vol. 23, no. 1, pp. 22–33, March 2016.

New Perception Approaches for Mobile Robots in Low Visibility Environments

Paul Fritsche, Björn Zeise, Patrick Hemme and Bernardo Wagner[1]

***Abstract*— In dangerous disaster operations, a mobile robot can gather first impressions of the environment. However, smoke and dust lead easily to disorientation while navigating with the help of traditional sensors, like RGB cameras and laser scanners. In SmokeBot, an EU-funded research project, we focus on the development of fusion strategies, in order to be able to navigate mobile robots manually and autonomously through harsh situations. We are currently working on sensor fusion between laser, radar, and thermal imaging camera in order to generate models of an environment, which are useful for disaster operation planning.**

I. Motivation and Problem Definition

Laser scanners and RGB cameras have established themselves as state of the art for mobile robotics, but they can only partially be applied in environments as shown in Fig. 1. Radar scanners and thermal imaging cameras overcome the aforementioned conditions, but come along with other problems. For example, the resolution and accuracy of a radar scanner is lower than that of a laser scanner. Thermal images contain reflections which lead to misinterpretation by the operator. Furthermore, the estimated temperature of a thermal imaging camera depends on the material of an object and needs corrections.

II. Related Work

The first appearance of radar sensors in the robotic community is tracing back to the Australian Centre for Field Robotics (ACFR) in the nineties, where fundamental work on probabilistic SLAM (EKF-SLAM) algorithms in combination with radar was developed [1]. Also, they built their own radar scanner [2]. Besides the ACFR, Adams et al. [3] were doing research on radar in robotics with the integration of the PHD filter and the application for mapping of mines. The PHD SLAM is working with a commercial NavTech device.

The removal of thermal reflections can be achieved either by hardware or software. One hardware-based solution is to suppress thermal reflections with the help of an infrared polarizing filter placed in front of the camera [4]. Besides expensive infrared filters, this technique requires a strict spatial setup between camera, filter, and object. The reflection handling method most relevant to our work is the use of the camera's changing point of view. An approach to this has been presented in [5].

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Fig. 1. Low visibility environments represent a challenge for traditional sensor modalities.

III. Own Approach and Contribution

In SmokeBot, we use a frequency modulated continuous wave radar (FMCW) scanner from the Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR), which we combine with a Velodyne VLP-16 laser scanner for modelling the environment. Our algorithm decides, whether to rely on the laser, the radar, or fuse both sensors. Additionally, our work brings contributions to the domain of thermography in mobile robotics. We developed algorithms which remove thermal reflections and correct temperature measurements of both dielectric and metal surfaces. Furthermore, we developed a new calibration setup between laser and thermal imaging camera to fuse a Velodyne VLP-16 and a FLIR A655sc.

Acknowledgment

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References

[1] S. Clark and G. Dissanayake, "Simultaneous localisation and map building using milimetre wave radar to extract natural features," *Internation Conference on Robotics and Automation*, 1999.

[2] S. Clark and H. D. Whyte, "The design of a high performance mmw radar system for autonomous land vehicle navigation," in *Field and Service Robotics*, 1998.

[3] M. Adams and E. Jose, *Robotic navigation and mapping with radar*. Artech House, 2012.

[4] S. Henke, D. Karstädt, K.-P. Möllmann, F. Pinno, and M. Vollmer, "Identification and suppression of thermal reflections in infrared thermal imaging," *Inframation Proc*, vol. 5, pp. 287–98, 2004.

[5] Y. Li and M. Brown, "Exploiting reflection change for automatic reflection removal," in *Proceedings of the IEEE International Conference on Computer Vision*, 2013, pp. 2432–2439.

Learning Task-Priorities based on a Mixture of Torque Controllers

Niels Dehio and Jochen J. Steil

Abstract— **Simultaneous mastering of multiple tasks during motion generation, as well as frequent switching between different tasks according to new environmental situations is challenging. Traditional null-space based approaches for redundant robots implement a strict, hierarchical prioritization for tracking multiple objectives. In consequence, these schemes are not suited to impose smooth priorities or changing them during motion execution. In comparison, a recently developed mixture of controller approach superposes torques from several control modules and thereby enables flexible adaption of priorities for pursuing different goals. Our main contribution is the development of a framework which allows for automatic derivation of suitable mixture coefficients which represent priorities. Additionally, we show that switching between tasks by smoothly blending the corresponding priorities during motion execution is feasible. The proposed framework is demonstrated for the full 11 DOF upper body of the compliant humanoid robot COMAN in simulation.**

Keywords: Motion Generation, Torque Control, Learning

I. Motivation and Problem Definition

Robots have recently become proficient in abilities such as efficient walking or catching objects in flight. While performing single tasks individually is technically solved for many skills, simultaneous tracking of multiple objectives as well as flexible adaption of task priorities is a persistent research question. The key challenge is to impose smooth priorities between multiple task objectives [1] and to adapt them during motion execution.

II. Related Work

Traditional null-space-based motion controllers based on inverse kinematics or inverse dynamics allow for tracking several objectives [2]. In such hierarchical schemes, high-priority tasks are executed directly, while low priority tasks are projected in the orthogonal null space with respect to the analytic solution of the primary task. This approach allows for precise and guaranteed execution of the primary goal e.g. reaching or manipulating an object, while secondary objectives (like joint limit avoidance) are handled within the null space. This scheme of strict hierarchy can not accommodate flexibility with respect to changing priorities easily. To overcome this shortcoming, more flexible schemes employ a soft prioritization between objectives, typically by means of a heuristic weighting in the task Jacobian [3], which takes place on a kinematic level.

One persistent research question is how to represent prioritization when applying torque-control. In this spirit, [4] proposed a torque-based *mixture of controller* approach that computes a weighted sum of torques, which arise from a multitude of atomic control modules. Each controller minimizes a different cost function which represents a particular objective, e.g. balancing, tracking or avoiding joint limits. This approach is flexible, however, at the cost of introducing several *mixture coefficients* in the torque superposition, which represent priorities and were manually chosen in [4].

III. Own Approach and Contribution

For generation of proper behavior, it is crucial to find a set of suitable mixture coefficients $\boldsymbol{\lambda}$. This constitutes a high-dimensional search problem. We treat the mixture coefficients $\boldsymbol{\lambda}$ as parameters of a policy, which computes for each generalized robot state an action (torques) and transforms the current state into a consecutive state through motion generation. We employ the state-of-the-art CMA-ES (Covariance Matrix Adaptation Evolution Strategy) [5] for policy improvement with respect to a cost function in [6].

Applying this framework, priorities for the underlying control modules can easily be learned offline. We show the ability to transfer the learned policy to new tasks, which were not part of the optimization process. Furthermore, we adapt mixture coefficients online to react to environmental changes. To pursue new tasks, we choose priorities according to our previous optimization experiments and smoothly blend them to enable smooth transitions. We demonstrate our approach with the COMpliant huMANoid COMAN in simulation.

Acknowledgment

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References

[1] R. Lober, V. Padois, and O. Sigaud, "Variance Modulated Task Prioritization in Whole-Body Control," in *IEEE/RSJ Intern. Conf. on Intelligent Robots and Systems*, 2015, pp. 3944–3949.

[2] O. Khatib, "A Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation," *IEEE Journal of Robotics and Automation*, vol. 3, no. 1, pp. 43–53, 1987.

[3] B. Dariush, M. Gienger, B. Jian, C. Goerick, and K. Fujimura, "Whole Body Humanoid Control From Human Motion Descriptors," in *IEEE Intern. Conf. on Robotics and Automation*, 2008, pp. 2677–2684.

[4] F. L. Moro, M. Gienger, A. Goswami, N. G. Tsagarakis, and D. G. Caldwell, "An Attractor-based Whole-Body Motion Control (WBMC) System for Humanoid Robots," in *IEEE/RAS Intern. Conf. on Humanoid Robots*, 2013.

[5] N. Hansen and A. Ostermeier, "Completely Derandomized Self-Adaptation in Evolution Strategies," *Evolutionary Computation*, vol. 9, no. 2, pp. 159–195, 2001.

[6] N. Dehio, R. F. Reinhart, and J. J. Steil, "Multiple Task Optimization with a Mixture of Controllers for Motion Generation," in *IEEE/RSJ Intern. Conf. on Intelligent Robots and Systems*, 2015, pp. 6416–6421.

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Incremental Bootstrapping of Parametrized Skill Memories

J. F. Queißer and J. J. Steil*

***Abstract*— The optimization of policies for motion generation suffers from complex reward surfaces. Repeated policy optimization for parameterized tasks introduces additional complexity and has been previously addressed by estimation of mappings from task to policy parameters. In this ongoing work, we introduce a method that estimates those mappings incrementally. Our approach combines iterative learning with state-of-the-art black box policy optimization. We investigate the benefits of learning parametrized skills for efficient retrieval of task-parameterized policies. As well as the reduction of number of roll-outs when optimizing policies for novel tasks.**

I. Motivation and Problem Definition

Advanced robotic systems face non-static environmental conditions which require context-dependent adaptation of motor skills. Approaches that optimize parameters for a given task, like trajectory estimation [1], are only able to deal with static tasks. Although in many cases a low-dimensional parametrization that covers the variance of a task exists. For example, consider a reaching task that has to incorporate different obstacle positions and reaching targets. A full optimization for each new task from a reasonable initialization, that was acquired by e.g. kinesthetic teaching, means that many computations and trials need to be performed before the task can be executed.

II. Related Work

Previous work successfully achieved throwing of objects at parametrized target positions [2] or playing table tennis using motion primitives that are parameterized with respect to the current ball trajectory [3]. While learning in [4], [5], [6] was conducted offline on precollected data sets, e.g. collected from human demonstrations, the work in [2] integrates an active learning criterion in order to select new task parameterizations in unexplored areas of the memory to enhance efficiency of skill memory acquisition. But generation of training data for skill memories requires a set of optimized samples, which is costly since each action has to be performed on the robot. Each training sample is based on a full optimization with a fixed initialization or an initialization gathered by demonstration e.g. kinesthetic teaching.

III. Own Approach and Contribution

In our work (sumitted to *International Conference on Humanoid Robots*, [7]), we follow the idea of [2] to apply dedicated policy optimization for new task parameterizations. We propose an algorithm for an iterative bootstrapping of such skill memories that results in a speed up of the optimization processes triggered for novel task parameterizations. In contrast to [2] we propose an initialization of the optimizer by the current guess of a iteratively enhanced skill memory. This allows for an bootstrapping process of the memory. We achieve this by utilizing online learning so that an gradually enhanced guess of the skill memory results in a reduced number of rollouts needed for optimization to solve new tasks. Therefore we focus in this work on the benefits of consolidating previous experience in form of a parametrized skill memory. For policy optimization, we apply the black box optimization algorithm CMA-ES [8]. We show systematically that the optimization process benefits from the initial condition proposed by the not yet fully trained parameterized skill and how this benefit depends on the model complexity of the learning algorithm. We evaluate the proposed approach on a via point task with a planar 10 DOF robot arm. The scalability of the approach is demonstrated by bootstrapping a parametrized skill for a humanoid robot scenario. The latter experiment targets a reaching task incorporating the upper body kinematics of the COMAN robot in a constrained environment.

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References

[1] F. Günter, "Using reinforcement learning for optimizing the reproduction of tasks in robot programming by demonstration," Ph.D. dissertation, STI, Lausanne, 2009.

[2] B. C. da Silva, G. Baldassarre, G. Konidaris, and A. Barto, "Learning parameterized motor skills on a humanoid robot," in *IEEE Intern. Conf. Robotics and Automation*, 2014, pp. 5239–5244.

[3] J. Kober, A. Wilhelm, E. Oztop, and J. Peters, "Reinforcement learning to adjust parametrized motor primitives to new situations," *Autonomous Robots*, vol. 33, pp. 361–379, 2012.

[4] T. Matsubara, S.-H. Hyon, and J. Morimoto, "Learning parametric dynamic movement primitives from multiple demonstrations." *Neural Networks*, vol. 24, no. 5, pp. 493–500, 2011.

[5] F. Stulp, G. Raiola, A. Hoarau, S. Ivaldi, and O. Sigaud, "Learning compact parameterized skills with a single regression," in *IEEE-RAS Intern. Conf. on Humanoid Robots*, 2013, pp. 417–422.

[6] R. F. Reinhart and J. J. Steil, "Efficient policy search in low-dimensional embedding spaces by generalizing motion primitives with a parameterized skill memory," *Autonomous Robots*, vol. 38, no. 4, pp. 331–348, 2015.

[7] J. F. Queisser, R. F. Reinhart, and J. J. Steil, "Incremental bootstrapping of parametrized skill memories," in *IEEE-RAS Intern. Conf. on Humanoid Robots*, submitted for publication 2016.

[8] N. Hansen and A. Ostermeier, "Adapting arbitrary normal mutation distributions in evolution strategies: the covariance matrix adaptation," in *Proceedings of IEEE Intern. Conf. on Evolutionary Computation*. IEEE, 1996, pp. 312–317.

Perception of Affordances for Whole-Body Loco-Manipulation

Peter Kaiser, Markus Grotz, Eren E. Aksoy and Tamim Asfour

***Abstract*— The perception of whole-body affordances in unknown environments is an essential prerequisite for autonomous humanoid robots. Whole-body affordances are possibilities of environmental interaction, referring to actions of whole-body locomotion or manipulation. Examples for such actions are *leaning* against walls, *pushing* or *lifting* large objects. We developed a perceptual pipeline for the extraction of such affordances based on a simplified representation of the environment starting from RGB-D camera images. The feasibility of this approach has been demonstrated in various examples in simulation as well as on real robotic platforms.**

I. Motivation and Problem Definition

Humanoid robots that are intended to operate in unstructured, human-centered environments require a rich perceptual basis for identifying possible ways of interaction with environmental objects. Actions of whole-body locomotion and manipulation play an important role for the utilization of structures designed for the human body, e.g stairs or ladders. The goal of the presented work is the design and implementation of a perceptual pipeline for the extraction of whole-body affordances from a perceived unknown environment.

II. Related Work

The theory of *affordances* [1] states that an agent perceives action possibilities based on properties of relevant environmental objects and based on its own capabilities. Overviews over applications of affordances in robotics can be found in [2] and [3]. In this work we specifically focus on the concept of *whole-body affordances*, i.e. affordances that refer to actions of whole-body locomotion or manipulation. This includes actions for whole-body stabilization or large-scale manipulation.

Many of the teams participating in the DARPA Robotics Challenge (DRC) pursued an affordance-driven approach to whole-body locomotion and manipulation. The perceptual process as well as the execution of actions were supervised by human operators via teleoperation in a semi-autonomous fashion. An overview over such shared autonomy interfaces can be found in [4].

III. Own Approach and Contribution

Fig. 1 shows the structure of the perceptual pipeline from RGB-D sensor information to the extraction of whole-body affordances. The extraction of affordances works based on an intermediate simplified representation of the scene in terms of planes, cylinders and spheres. In an hierarchical process we derive continuous *affordance certainty functions* $\Theta(\pi, \boldsymbol{x}) \in [0, 1]$ that estimate the existence of an affordance for a given primitive π and a given end-effector pose $\boldsymbol{x}$.

Fig. 2 shows an exemplary evaluation of the system in a valve turning task. As the affordance certainty functions are purely derived from visual perception, we consider them to represent *affordance hypotheses* that are always subject to validation by the robot.

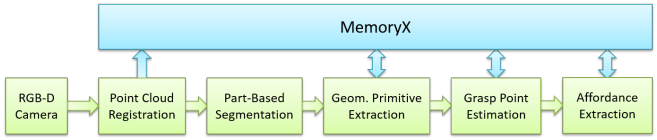

Fig. 1: The perceptual pipeline for affordance extraction [5], [6]. The scene perceived with an RGB-D camera is segmented into environmental primitives which form the basis for the extraction of whole-body affordances.

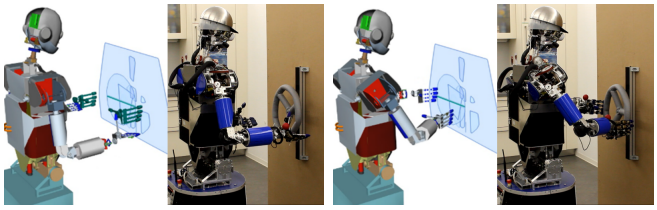

Fig. 2: The perceptual pipeline extracts bimanual affordances and proposes end-effector poses for the subsequent action execution in a valve turning scenario.

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References

[1] J. J. Gibson, *The Ecological Approach to Visual Perception*, 1978.

[2] E. Şahin, M. Çakmak, M. R. Doğar, E. Uğur, and G. Üçoluk, "To Afford or Not to Afford: A New Formalization of Affordances Toward Affordance-Based Robot Control," vol. Adaptive Behavior, no. 15, p. 447, 2007.

[3] N. Krüger, C. Geib, J. Piater, R. Petrick, M. Steedman, F. Wörgötter, A. Ude, T. Asfour, D. Kraft, D. Omrčen, A. Agostini, and R. Dillmann, "Object-Action Complexes: Grounded Abstractions of Sensorimotor Processes," *Robotics and Aut. Sys.*, vol. 59, no. 10, pp. 740–757, 2011.

[4] R. R. Murphy, "Meta-analysis of Autonomy at the DARPA Robotics Challenge Trials," *J. of Field Rob.*, vol. 32, no. 2, pp. 189–191, 2015.

[5] P. Kaiser, D. Gonzalez-Aguirre, F. Schültje, J. Borràs, N. Vahrenkamp, and T. Asfour, "Extracting Whole-Body Affordances from Multimodal Exploration," in *IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, 2014, pp. 1036–1043.

[6] P. Kaiser, M. Grotz, E. E. Aksoy, M. Do, N. Vahrenkamp, and T. Asfour, "Validation of whole-body loco-manipulation affordances for pushability and liftability," in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, 2015.

Analytical Forward and Inverse Kinematics of a Multi-Flexible-Link Robot Arm under Gravity

Freia Irina Mues[1], Myrel Alsayegh[1], Jörn Malzahn[2] and Torsten Bertram[1]

***Abstract*— Lightweight robots with flexible links suffer from oscillatory behaviour as well as load related deflections. These effects drastically complicate the derivation and generalization of analytical solutions to the forward and inverse kinematics. Two approaches to address this challenge are presented along with experimental results for a 3 DOF multi-flexible-link robot arm. The analytical approaches are referenced against a previously developed data based solution.**

I. Motivation and Problem Definition

Since 1974 literature considers link elasticity in industrial and space applications. This is due to the necessity of a high payload-to-weight ratio and enlarged workspaces. Additionally elastic robot arms display inherent safety features during physical interaction with their environment. Their intrinsic compliance can even be exploited "to grant elastic link robots force sensing capabilities" [1].

On the other hand link-elastic arms come with disadvantages of vibrations and static deflections. While many publications deal with vibration damping of link-elastic structures, the solution to the forward and inverse kinematics in the presence of static deflections has barely been addressed in literature. The forward and inverse kinematics are well known topics for rigid robots, but still hold substantial challenges for flexible arms operating under gravity.

II. Related Work

Recently, issues of controlling and applying lightweight robot arms have been focused on. The most probed control aspects therein are oscillation damping and end effector control [1]. Though a lot of theoretical control methods are available nowadays, most of them need very accurate models of the system. Many works in literature consider only single flexible links and/or exclude gravitational influence [1]. In [2] the authors propose a promising approach using neural networks to solve the forward and inverse kinematics, but neural networks in general cannot provide the same insight as an analytical solution.

III. Approach and Contribution

For this reason, two approaches to solve the analytical forward and inverse kinematics are derived for the three DOF (**D**egrees **O**f **F**reedom) flexible link robot arm TUDOR (**T**echnical **U**niversity of **D**ortmund **O**mni-elastic **R**obot, see figure 1). Both describe the discrepancy between the desired position and the current one as a virtual spring. While the first approach implements a linear spring, the second uses a rotational one.

Gravitational forces and varying payloads are considered, whereas an oscillation damping is already at hand. The absolute accuracy, repeatability and robustness of the analytical approaches are compared to the forward and inverse kinematics of a previously developed data based approach [2], which serves as a reference. To evaluate the approaches a MoCap (**Mo**tion **Cap**ture system) is employed for ground truth measurements of the end effector position. The results show unexpected deviations of the experimental system, hence the accuracy of all examined approaches is limited. Though they provide a high goodness of fit above 84 %, improvements are suggested to increase the accuracy. The second analytical approach is found to be the most accurate and reliable one among the examined approaches.

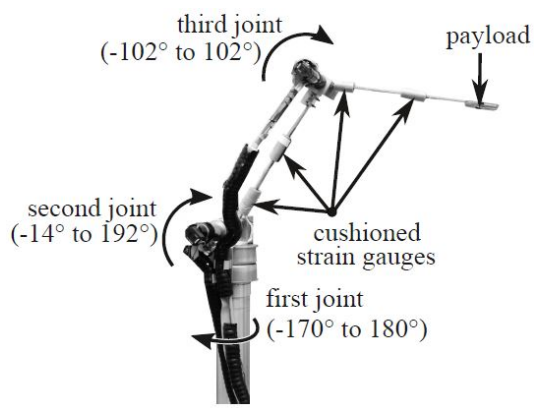

Fig. 1. Experimental system TUDOR [3]

References

[1] D.-I. J. Malzahn, "Modeling and control of multi-elastic-link robots under gravity," Ph.D. dissertation, TU Dortmund University, 2014.

[2] A. S. Phung, J. Malzahn, F. Hoffmann, and T. Bertram, "Data based kinematic model of a multi-flexible-link robot arm for varying payloads," in *Robotics and Biomimetics (ROBIO), 2011 IEEE International Conference on*. IEEE, 2011, pp. 1255–1260.

[3] J. Malzahn, R. Schloss, and T. Bertram, "Link elasticity exploited for payload estimation and force control," in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*. IEEE, 2015, pp. 1508–1513.

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Indoor Scene Recognition by 3D Object Search for Robot Programming by Demonstration

Pascal Meißner and Rüdiger Dillmann

***Abstract*— We present an approach for recognizing indoor scenes in object constellations that require object search by a mobile robot, as they cannot be captured from a single viewpoint. In our approach that we call Active Scene Recognition (ASR), robots predict object poses from learnt spatial relations that they combine with their estimates about present scenes. The models that we present for estimating scenes and predicting poses are trees of Implicit Shape Models (ISMs). We extract scene models from object configurations that are acquired during demonstration of actions, characteristic for a certain scene. We introduce an approach that uses combinatorial optimization to decide which spatial relations between objects are relevant to accurately describe an indoor scene, thereby generating an optimal ISM tree representation for the scene.**

I. Motivation and Problem Definition

Research in Programming by Demonstration (PbD) intends to enable non-experts to teach robots how to execute every day actions in indoor scenarios. For a robot to perform learnt actions autonomously, it does not suffice to teach a description of the action itself. The robot also needs capabilities to decide whether an action is appropriate in a given context or not. For a robot to assess its environment by interpreting spatial object configurations, models of the scenes are required. To provide robots with real-time scene recognition capabilities, we introduce a variant of the Implicit Shape Model (ISM) that represents spatial relations as six Degree-of-Freedom (DoF) coordinate transforms between objects. Objects in indoor scenes may be distributed or occluded. Object configurations often have to be perceived from several viewpoints before a scene can be recognized. Without prior knowledge, which perspectives have to be checked for which objects, the 6 DoF space of camera viewpoints has to be browsed by uninformed search. Such an approach is infeasible due to combinatorial explosion. For a more efficient search with prior knowledge, we present Active Scene Recognition (ASR) that, given a partially recognized scene, predicts poses for the remaining objects, not yet found, with the same relations, used for recognition. Jointly recognizing scenes and predicting poses with relations enables to identify object constellations independent of their absolute locations.

II. Related Work

Methods in indoor scene understanding as [1] often use Qualitative Spatial Relations (QSRs). Being a symbolic abstraction, QSRs perform well in generalizing object relations, while lacking a detailed description of relative object locations, as we require. In contrast, ISMs [2] are a non-parametrical method that model relations in any complexity. Besides how to model spatial relations, another question is which relations among objects should be represented in a scene. Little work [3], [4] is devoted to this issue and only covers special cases of sets of relations (topologies). Most methods in object search, simplify search to estimating Next-Best-Views (NBVs). Current work as [5] employs QSRs and searches a single object instead of object configurations.

III. Own Approach and Contribution

For meeting the requirements of PbD in scene recognition, we extend ISMs to process 6 DoF poses instead of 3D data. ISMs are limited to represent scenes as relation topologies that are star-shaped, leading to false positives during scene recognition. To model other relation topologies, we introduce a representation of trees of ISMs as well as a method to convert any connected relation topology into an ISM tree using a heuristic depth-first-search. It allows using complete graphs as scene models. Despite causing no false positives, they are intractable for scene recognition. To achieve efficiency, we contribute a combinatorial optimization that searches for an optimal relation topology by traversing the space of connected topologies, for a given set of objects. We realize our ASR concept by recognizing scenes with ISM trees in an object search loop. This system selects positions and orientations of NBVs for a mobile robot with a pivoting head. We contribute a particle filter-based approach for predicting object poses with ISM trees and a NBV estimation on predicted poses, optimizing 6 DoF viewing frustums. To prevent combinatorial explosion in evaluating NBV candidates, we introduce a hierarchical approach to sample potential robot positions. Usually, view candidates are evaluated by counting predicted object positions in them. Instead, we evaluate the confidence of correct object detection for each prediction.

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References

[1] D. Lin, S. Fidler, and R. Urtasun, "Holistic scene understanding for 3d object detection with rgbd cameras," in *Int. Conf. on CV*, 2013.

[2] B. Leibe, A. Leonardis, and B. Schiele, "Robust object detection with interleaved categorization and segmentation," *Int. Journal of CV*, 2008.

[3] G. Carneiro and D. Lowe, "Sparse flexible models of local features," in *Euro. Conf. on Computer Vision*, 2006.

[4] D. Crandall, P. Felzenszwalb, and D. Huttenlocher, "Spatial priors for part-based recognition using statistical models," in *Conf. on Computer Vision and Pattern Recognition*, 2005.

[5] L. Kunze, K. K. Doreswamy, and N. Hawes, "Using qualitative spatial relations for indirect object search," in *Int. Conf. on Robotics and Automation*, 2014.

Haptic learning and haptic search for complex shapes

Alexandra Moringen and Helge Ritter

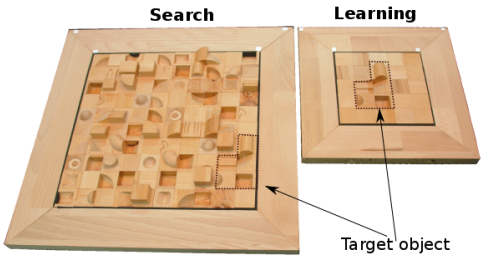

Fig. 1. MHSB enables generation of known and unknown shape patterns.

***Abstract*— Haptics is a very important interaction modality for humans and robots alike. Motivated by the goal to endow multi-fingered anthropomorphic robots (e.g. [1]) with improved strategies for haptic exploration and learning, we have devised an experimental setting for studying haptic search for and learning of complex shapes by human subjects. A new key element of the approach is a modular haptic stimulus board (MHSB) that allows to systematically vary complex shape patterns at different levels and to analyze the resulting haptic search behavior. We found that a simultaneous execution of multiple exploratory procedures split among the hand and the fingers enables a parallel access to several shape properties at a given point in time. Second evaluation of haptic search suggested a prevailing parameterization of the executed exploratory procedures w.r.t. the shape features of the target object. Our long-term goal is to generate motion instructions for a robotic arm and hand to perform a search task based on tactile feedback, exploiting the findings of this research.**

Multi-fingered haptic interaction, unknown complex shapes, multimodal data analysis.

I. Motivation and Problem Definition

Humans and robots share a need for reliable and robust information about physical contact with surfaces of widely varying shape, rigidity and friction. Compared to vision, research on haptic interaction, including important skills such as search and learning, is still very sparse – despite groundbreaking early works, such as Klatzky et al. [2]. Parameterization as well as the spatiotemporal structure of haptic exploration of complex shapes is still an open research question and is a focus of our work.

II. Related Work

Building upon earlier frameworks used for research on haptic saliency we have designed a novel modular haptic stimulus board (MHSB). It allows to generate shape stimuli which can be conveniently and systematically varied across wide range of complexity (see Figure 1). To analyze the haptic interaction of study participants with the MHSB, we employ finger and hand motion tracking technology, including a 13-camera Vicon setup, a microphone, and a tactile data-glove with fabric-based sensors [3]. A video of one experimental run is available online[1].

III. Own Approach and Contribution

In [4], [5][2] we have investigated spontaneous haptic search in a scenario in which both the search target and the search field are represented by a random composition of different elementary shapes. Blindfolded sighted individuals were asked, firstly, to memorize a complex search target presented only haptically and in isolation, and, secondly, to find this search target embedded in a larger, encompassing search field (see Figure 1). Based on a detailed multimodal data capture of the hand and fingers, we focused on the mechanisms that influence the efficiency of the haptic search. We have used three-dimensional Vicon trajectories of the fingers and the hand, as well as the pressure values applied by the fingers for the data analysis. We have used the Basler camera and the microphone recordings for the annotation. Our results were two-fold. Firstly, we have found that during haptic search typically a mixture of exploratory procedures is used at a given point of time [5]. Mixture components are distributed among fingers and the hand and are executed in parallel, enabling a simultaneous access to different shape properties. Secondly, we have investigated an influence of different complex shape features on the strategy of exploration [4]. A new direction of our current work is a computational approach to identifying shape properties based on haptic and kinematic data.

References

[1] G. Buscher, M. Meier, G. Walck, R. Haschke, and H. J. Ritter, "Augmenting curved robot surfaces with soft tactile skin," in *Intelligent Robots and Systems (IROS)*, 2015, pp. 1514–1519.

[2] R. L. Klatzky, S. J. Lederman, and C. L. Reed, "There's more to touch than meets the eye: the salience of object attributes for hpatics with and without vision," *Journal of Experimental Psychology*, 1987.

[3] G. Buescher, R. Koiva, C. Schuermann, R. Haschke, and H. Ritter, "Tacile dataglove with fabric-based sensors," in *Proc. Humanoids*, 2012, pp. 204–209.

[4] K. Krieger, A. Moringen, R. Haschke, and H. Ritter, "Shape features of the search target modulate hand velocity, posture and pressure during haptic search in a 3d display," in *Lecture Notes in Computer Science*. Springer, 2016.

[5] A. Moringen, R. Haschke, and H. Ritter, "Search procedures during haptic search in an unstructured 3d display," in *IEEE Haptics Symposium*, 2016.

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[2] Both papers are available online: http://www.techfak.uni-bielefeld.de/persons/abarch/{abstract.pdf,paper.pdf}

Spatial investigation of biologic joints by robotic arms

Constantin von Deimling[1], Peter Föhr[1], Andreas Obermeier[1], Arne Hildebrandt[2], Christoph Schütz[2], Felix Sygulla[2], Oliver Hofmann[2], Daniel Wahrmann[2], Robert Wittmann[2], Daniel Rixen[2] and Rainer Burgkart[1]

***Abstract*— The increasing medical market caused the development of a huge variety of implants aiming to restore mobility. Their mechanical evaluation within the body is not obligatory, therefore the endoprostheses' actual behaviour is often unpredictable. We believe that a more detailed spatial investigation of joint treatments is needed to avoid implant failure. Hence, we like to utilize robotic arms to palpate biologic joint specimens and characterize the kinematic differences to endoprosthetic implants.**

Keywords: Robotic arms, Biomechanical Testing, Endoprostheses

I. Motivation and Problem Definition

In recent years, a growing number of increasingly younger patients undergo surgery of the musculoskeletal system to regain mobility or to relieve pain. For this purpose a wide variety of different implants like endoprostheses or fixators have been developed and are in clinical use. While the biocompatibility of these devices is extensively tested, the required mechanical investigation is limited to uni-axial testing standards [1]. Their spatial behaviour within the body is often unknown. Novel studies proved that many of the developed implants do not fulfil the patient's expectations and even endanger them, by failing within the body [2]. To improve them, it is necessary to gain knowledge about the spatial biomechanical behaviour of joints. Therefore we want to use robotic arms to investigate the kinematic behaviour of native joints and compare it with endoprosthetic treated joints.

II. Related Work

Biologic joints present a complex nonlinear contact problem. The kinematics are unique for every specimen and cannot be substituted by ideal geometries. Since the elasticity of joints is limited, pure position control cannot be applied to investigate differing joint kinematics. To overcome this challenge it is possible to employ explicit force control for the actuation of spinal specimen [3]. Nonetheless, this approach has limited stability and is not suitable to articulate unstable systems, like the knee, hip or shoulder joint [4]. Hybrid parallel position force control has proven to be useful in comparable industrial applications [5]. But in the field of biomechanics, it is not possible to input consistent trajectories containing forces, moments, positions, and orientations. *Shweikeh* concluded in 2014 that all known robotic test rigs used for spinal analysis, were still in the early development phase, and no real gold standard has established yet [6].

III. Own Approach and Contribution

We are confident that growing computational capabilities and new approaches like hardware-in-the-loop [7] may help solving some of the challenges bound to spatial investigation of biologic joints. To articulate joint specimens, we use a robotic arm (Stäubli RX90B, Switzerland) in an open software architecture (MATLAB/Simulink, USA) while reaction forces and moments (JR3, USA) are measured at its end effector. Thereby we are able to develop various control architectures and adaptive trajectory planning, that allow us to investigate different joints. In our presentation we like to give an overview over the setup, the control approaches and the adaptive trajectory planning, that we use for biomechanical testing of knee specimens and endoprostheses.

References

[1] ISO, "Physico-chemical, morphological and topographical characterization of materials," International Organization for Standardization, ISO/TS 10993-19, 2006.

[2] M. J. Nieuwenhuijse, R. G. Nelissen, J. W. Schoones, and A. Sedrakyan, "Appraisal of evidence base for introduction of new implants in hip and knee replacement: a systematic review of five widely used device technologies," *BMJ (Clinical research ed.)*, vol. 349, p. g5133, 2014.

[3] H. Martinez, T. Obst, H. Ulbrich, and R. Burgkart, "A novel application of direct force control to perform in-vitro biomechanical tests using robotic technology," *Journal of Biomechanics*, vol. 46, no. 7, pp. 1379–1382, 2013.

[4] Y. Xu, J. M. Hollerbach, and D. Ma, "A nonlinear pd controller for force and contact transient control," *IEEE Control Systems Magazine*, vol. 15, no. 1, pp. 15–21, 1995.

[5] M. H. Raibert and J. J. Craig, "Hybrid position/force control of manipulators," *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, vol. 103, no. 2, pp. 126–133, 1981.

[6] F. Shweikeh, J. P. Amadio, M. Arnell, Z. R. Barnard, T. T. Kim, J. P. Johnson, and D. Drazin, "Robotics and the spine: a review of current and ongoing applications," *Neurosurgical focus*, vol. 36, no. 3, p. E10, 2014.

[7] S. Herrmann, D. Kluess, M. Kaehler, R. Grawe, R. Rachholz, R. Souffrant, J. Zierath, R. Bader, and C. Woernle, "A novel approach for dynamic testing of total hip dislocation under physiological conditions," *PloS one*, vol. 10, no. 12, p. e0145798, 2015.

* The authors declare that they have no conflict of interest regarding this conference contribution

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Using Human Demonstrations and Trajectory Optimization for Generalizable Human-like Robot Motions

Dorothea Koert, Guilherme Maeda, Rudolf Lioutikov, Gerhard Neumann and Jan Peters

***Abstract*— Learning motions out of human demonstrations provides an intuitive way for inexperienced users to teach tasks to a robot. As such, robots must be endowed with the ability to generalize motions to different workspaces, e.g. to avoid obstacles not present during such demonstrations. Towards this goal our work proposes a unified method to (1) generalize robot motions to different workspaces via trajectory optimization while leveraging on human demonstrations, and (2) to locally adapt and reuse the optimized solution to quickly satisfy desired via points using a probabilistic representation of movement primitives. We validate the method using a 7 DoF lightweight arm that grasps and places a ball at different boxes while avoiding obstacles that were not present during the original human demonstrations.**

I. Motivation and Problem Definition

The future generation of collaborative robots will invariably face a variety of unforeseen tasks; rendering manual pre-programming of motions unrealistic in practice. Our method comprises two steps, the off-line optimization of the human demonstrations as a collision-free distribution, and the real-time use (and reuse) of this optimized distribution to satisfy specific task constraints. The method is evaluated in a pick-and place scenario where a ball is supposed to be grasped and delivered to boxes at different locations. Figure 1 illustrates the human demonstrations in an obstacle-free environment at the left and the generalization of the robot motion at the right. Moreover, the robot is required to adapt its motion to place the ball inside boxes not shown in the demonstrations.

II. Related Work

The adaptation and generalization of robot motions have been successfully achieved by local trajectory optimization methods [1]. Ye and Alterovitz present a framework to extract certain constraints out of human motions based on the variance in the motions [2]. Their approach uses the distribution of demonstrations as an input but the final collision-free solution is reduced to a single trajectory. A way to preserve the full distribution during the optimization process is provided by using the Kullback-Leibler divergence as a metric to quantify deviations between the optimized solution and the original demonstrations [3]. Given a distribution of human demonstrations Probabilistic Movement Primitives (ProMPs) [4] allow for generation of adaptive trajectories but its original formulation does not address obstacle avoidance.

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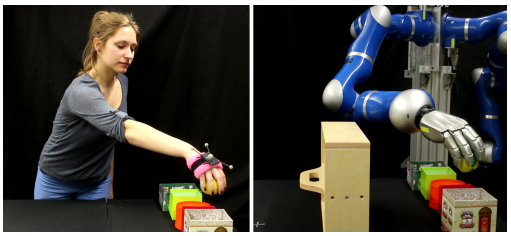

Fig. 1. Human demonstration and resulting robot motion

III. Own Approach and Contribution

Given a robot trajectory $\boldsymbol{x} = \{x^{[1]}, ..., x^{[T]}\}$ the proposed optimization addresses two principle objectives. First, it minimizes the deviation of the current policy p from the distribution of human demonstrations d using a KL-divergence and second, it maximizes a reward function $R(\boldsymbol{x})$ to avoid obstacles. To optimize the policy we extend the stochastic search Relative Entropy Policy Search and incorporate the two objectives as

$$\underset{\boldsymbol{\Theta}}{\text{argmax}} \sum_{x} p(\boldsymbol{x};\boldsymbol{\Theta})R(\boldsymbol{x}) - Bp(\boldsymbol{x};\boldsymbol{\Theta})\log\left(\frac{p(\boldsymbol{x};\boldsymbol{\Theta})}{d(\boldsymbol{x};\boldsymbol{\Theta_D})}\right),$$

where $\boldsymbol{\Theta}$ and $\boldsymbol{\Theta_D}$ denote the policy parameters of the new policy and the demonstrations, B trades off between minimal deviation from the demonstrated distribution and obstacle avoidance and $p(\boldsymbol{x};\boldsymbol{\Theta})$ and $d(\boldsymbol{x};\boldsymbol{\Theta_D})$ can bee seen as the likelihood of $\boldsymbol{x}$ under the distributions p or d.

The contribution of this work is an off-line optimization algorithm for motion planning that outputs trajectory distributions whose temporal and spatial correlations are extracted directly from human movements. The resulting obstacle free distributions are connected to the ProMP framework for real-time adaptation to task specific constraints such as via-points.

Acknowledgment

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References

[1] M. Kalakrishnan, S. Chitta, E. Theodorou, P. Pastor, and S. Schaal, "Stomp: Stochastic trajectory optimization for motion planning," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*. IEEE, 2011.

[2] G. Ye and R. Alterovitz, "Demonstration-guided motion planning," in *International symposium on robotics research (ISRR)*, vol. 5, 2011.

[3] P. Englert, A. Paraschos, M. P. Deisenroth, and J. Peters, "Probabilistic model-based imitation learning," *Adaptive Behavior*, vol. 21, no. 5, 2013.

[4] A. Paraschos, C. Daniel, J. R. Peters, and G. Neumann, "Probabilistic movement primitives," in *Advances in neural information processing systems*, 2013.

Model Predictive Control for Learning from Demonstration

Myrel Alsayegh, Frank Hoffmann and Torsten Bertram[1]

***Abstract*— In the context of Learning from Demonstration (LfD) the different reproduction schemes, specially the widely used Gaussian Mixture Regression (GMR) does not focus on the reproduction of a trajectory that complies to defined objective functions, like time optimality. While the use of Model Predictive Control (MPC) has proved its efficiency in generating a trajectory that complies to different optimality criteria in minimum time. We Propose to use the advantages of both concepts in a scheme that trades-off between generating a trajectory that reproduces the taught skill and the optimal trajectory with respect to the objective functions.**

I. Motivation and Problem Definition

Learning from Demonstration is a well established paradigm that allows for teaching robots different skills in an intuitive manner, in which a statistical model encoding the natural desired movements performed by the human is produced. This model is then utilized for reproduction under different situations or with diverse architectures [1]. The motion task is encoded with a Gaussian Mixture Model (GMM) which captures the probability of a data sample belonging to the underlying distribution of demonstrations. The reproduction of the intended skill rests upon Gaussian Mixture Regression (GMR), which not only provides a reference trajectory but also captures possible variations of the task. The robot might not be able to exactly reproduce the designated motion due to kinodynamic constraints, obstacles or disturbances. This observation demands a control scheme that reconciles the execution of the nominal task with the kinematic and dynamic capabilities of the robot and constraints imposed by the workspace. Model Predictive Control (MPC) in conjunction with GMR to trade-off reproduction of the skill with constraints and additional objectives of the robots motion promises a successful approach.

II. Related Work

The authors in [2] propose minimal intervention control for correcting those perturbations that interfere with task performance in a temporal sense using MPC. The definition of the task performance relies on a Hidden Semi-Markov Model (HSMM) movement duration profile constructed out of the different demonstrations. Nevertheless, the authors point out the difficulty of learning this duration profile which limits the applications of this proposed model. The introduced novel MPC approach is more general as it considers the entire trajectory rather than a limited horizon. For planning of time-optimal trajectories in the context of MPC, an innovative approach based on Timed Elastic Bands (TEB) for nonlinear time-optimal model predictive control is presented in [3]. Utilizing this scheme, the optimal trajectory is obtained by solving an optimization problem. In contrast to conventional MPC, the TEB based MPC incorporates the time intervals between the states explicitly as an optimization parameter.

III. Approach and Contribution

The introduced approach rests upon TEB originally conceived for online trajectory planning for mobile robots [3]. TEB generate a time optimal, collision free trajectory that is compliant with the robots kinodynamic capabilities. The combined approach exploits the advantages of both schemes, GMM and TEB-MPC for the purpose of synthesizing trajectories that imitate the task taught by demonstration and that are compliant with the integrity condition with respect to feasible controls. The TEB-MPC allows temporal variations of the skill without the need of an explicit duration model in comparison to [2]. The spatial-temporal variability of demonstrations is exploited in the elastic band which either adapts the path or the duration of the motion to achieve compliance with the kino-dynamic constraints or disturbances. The Gaussian mixture components are considered as attractors for the intermediate robot states of the TEB. The spatial and temporal variability represented by the related covariances of the GMM are considered as constraints. In this way, the intended skill described is integrated into the cost function of the MPC problem by a term:

$$J_{x,t}(B) = \sum_{i:T_i \geq t_{current}} ((x_i, T_i) - \mu_{\delta_i})^T \Sigma_{\delta_i}^{-1} ((x_i, T_i) - \mu_{\delta_i}) \tag{1}$$

in which (x_i, T_i) denote the states and time intervals of the TEB, and $\mu_{\delta_i}, \Sigma_{\delta_i}$ the mean and covariance of the Gaussian mixture component. δ_i denotes the Gaussian mixture component to which the i-th TEB state is associated. It is obtained by initializing the TEB states with GMR and selecting the nearest Gaussian. The approach is applied to the imitation of a pickup and drop task and its reproduction by a planar robot arm under constraints and disturbances.

References

[1] S. Calinon, *Robot Programming by Demonstration: A Probabilistic Approach*. EPFL/CRC Press, 2009, EPFL Press ISBN 978-2-940222-31-5, CRC Press ISBN 978-1-4398-0867-2.

[2] M. Zeestraten, S. Calinon, and D. G. Caldwell, "Variable duration movement encoding with minimal intervention control," *ICARA*, May 2016.

[3] C. Rösmann, F. Hoffmann, and T. Bertram, "Timed-elastic-bands for time-optimal point-to-point nonlinear model predictive control," *Control Conference (ECC), 2015 European*, pp. 3352–3357, July 2015.

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A multimodal capacitive sensor for Grasping and dexterous manipulation

Hosam Alagi[1]

***Abstract*— Starting from the state of the art requirements of HRI and grasping sensory and based on own works in the same branch a future work has been presented. The intention of this Work is to develop a low-cost multimodal capacitive sensor for Grasping and dexterous manipulation, which is capable to detect the proximity of objects in different modes and measure the normal and tangential forces in case of contact.**

I. Motivation and Problem Definition

The multimodality issue has recently become an interesting aspect for sensor systems for robot applications, in which flexible and integrated sensor are of advantage. Such a system should be able to register multi-physical events, such as, forces, vibration and the proximity of traced objects. Furthermore, it should be capable of extracting information about the geometry and the material of the object.

Those systems are advantageous not only in the field of human-robot interaction, where the accurate detection and interpretation of proximity and tactile events are essential for safety, but also for quasi-autonomous and dexterous grasping. Robust grasping and soft object manipulation a require variety of information about the object in all different phases: pre-grasping, grasping, manipulation and placement/handover.

II. Related Work

Diverse approaches for multimodal sensors and sensor systems have been presented. A dual-modality of detecting proximity and tactile events based on a capacitive measuring principle [1], [2] or combining different principles [3] is common in robotics. Additional features such as dynamic spatial resolution and sensing range have also been studied [4]. In the field of grasping and manipulation, 2D and 3D force sensors have been developed [5] [6], giving a grasping system advantages for handling complex tasks and providing haptic information about the object to be manipulated [7] [8]. Further processing of the sensor data can offer the possibility of identifying the material type of the objects [9] [10].

III. Own Approach and Contribution

This paper introduces future work on a novel approach for low-cost capacitive sensors, which combine a proximity measurement and measuring of force and torque in 3 dimensions. The idea is to develop an easy-to-integrate and low cost modular sensor, which provides the needed information for robust grasping starting with contactless preshaping. By implementing the self- and the mutual-capacitive mode for the proximity measurement, it is possible to preshape a gripper to non-conductive, conductive, grounded and not grounded objects. The pre-touch and touch based modalities will all be measured based on the capacitive principle. Such a monolithic measuring system would decrease the complexity of the sensor and increase the ability for integration in a robot system, e.g. gripper jaws. In addition, and in order to increase repeatability, a redundant and optional system based on a complementary measuring principle for the proximity measurement is considered.

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References

[1] H. K. Lee, S. I. Chang, and E. Yoon, "Dual-mode capacitive proximity sensor for robot application: Implementation of tactile and proximity sensing capability on a single polymer platform using shared electrodes," *IEEE Sensors Journal*, vol. 9, no. 12, pp. 1748–1755, Dec 2009.

[2] D. Göger, H. Alagi, and H. Wörn, "Tactile proximity sensors for robotic applications," in *Industrial Technology (ICIT), 2013 IEEE International Conference on*, Feb 2013, pp. 978–983.

[3] H. Hasegawa, Y. Mizoguchi, K. Tadakuma, A. Ming, M. Ishikawa, and M. Shimojo, "Development of intelligent robot hand using proximity, contact and slip sensing," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, May 2010, pp. 777–784.

[4] H. Alagi, S. E. Navarro, M. Mende, and B. Hein, "A versatile and modular capacitive tactile proximity sensor," in *2016 IEEE Haptics Symposium (HAPTICS)*, April 2016, pp. 290–296.

[5] R. Sargeant, H. Liu, L. D. Seneviratne, and K. Althoefer, "An optical multi-axial force/torque sensor for dexterous grasping and manipulation," in *Multisensor Fusion and Integration for Intelligent Systems (MFI), 2012 IEEE Conference on*, Sept 2012, pp. 144–149.

[6] H. K. Lee, J. Chung, S. I. Chang, and E. Yoon, "Normal and shear force measurement using a flexible polymer tactile sensor with embedded multiple capacitors," *Journal of Microelectromechanical Systems*, vol. 17, no. 4, pp. 934–942, Aug 2008.

[7] H. Liu, X. Song, J. Bimbo, L. Seneviratne, and K. Althoefer, "Surface material recognition through haptic exploration using an intelligent contact sensing finger," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct 2012, pp. 52–57.

[8] X. Song, H. Liu, K. Althoefer, T. Nanayakkara, and L. D. Seneviratne, "Efficient break-away friction ratio and slip prediction based on haptic surface exploration," *IEEE Transactions on Robotics*, vol. 30, no. 1, pp. 203–219, Feb 2014.

[9] N. Kirchner, D. Hordern, D. Liu, and G. Dissanayake, "Capacitive sensor for object ranging and material type identification," *Sensors and Actuators A: Physical*, vol. 148, no. 1, pp. 96 – 104, 2008.

[10] S. Mühlbacher-Karrer, A. Gaschler, and H. Zangl, "Responsive fingers capacitive sensing during object manipulation," in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*, Sept 2015, pp. 4394–4401.

Decentralized Data-Driven Control for Environmental Monitoring by Cooperating Sensor-Equipped UAVs

Juliane Euler[1] and Oskar von Stryk[1]

Abstract— **In scenarios involving atmospheric dispersion of hazardous material, using unmanned aerial vehicles (UAVs) as mobile and flexibly deployable sensor platforms can be extremely helpful for the collection of measurement data required to accurately assess the situation. The use of multiple cooperating UAVs controlled in an optimal manner offers even higher performance and efficiency.**

This work presents a decentralized optimization-based approach to cooperative data-driven control of multiple sensor-equipped UAVs. It combines optimum design, parameter estimation, and model-predictive cooperative control in a repeating sequential procedure. That way, the loop between process identification and vehicle control is closed, resulting in efficient and adaptive sensor motion that is essential for estimating highly-dynamic and large-scale processes like atmospheric dispersion.

The approach is implemented in ROS and simulations in Gazebo prove its applicability and performance in different single- and multi-objective monitoring scenarios.

I. Motivation and Problem Definition

The use of robotic systems for environmental monitoring offers obvious benefits as they can gather important information even if the setting is hostile and possibly life-threatening for humans. Moreover, mobile sensors offer higher local precision, flexibility, and efficiency than stationary sensor networks. However, large-scale dynamic spatiotemporal processes can hardly be captured by a single mobile sensor. Therefore, cooperative monitoring by a group of sensor equipped vehicles is investigated in this work.

In order to assess possible consequences of an atmospheric dispersion process, the parameters of a simulation model of the process need to be identified based on measurement data gathered by the sensors. Outcome and efficiency of the measurement process can be maximized using an adaptive path planning approach that accounts for already available information as well as the vehicles' individual motion capabilities. This can be done by not only using new measurement data to update the parameter estimate, but by feeding the estimate back to the vehicles' motion controller in order to maximize the information gain of future measurements.

II. Related Work

Closing the loop between simulation and measurements is characteristic for *Dynamic Data Driven Application Systems* (DDDAS). DDDAS implementations that explicitly account for the sensor platforms' motion dynamics are typically set up as a complex optimal control problem (OCP) that optimizes some estimation quality measure subject to ordinary differential equations representing the vehicle dynamics [1]. However, online adaptability to the gathered information is not possible in a feedforward approach and solving the OCP is computationally intensive. Therefore, [2] and [3] propose to repeatedly solve the OCP in a receding horizon fashion, but both approaches still depend on a central computing instance. As communication is likely to be limited in real-world applications, though, decentralized solutions are preferable and offer beyond that better scalability.

III. Own Approach and Contribution

The proposed decentralized approach is based on optimum design and optimal vehicle control, but in order to increase computational efficiency towards a possible real-time deployment, both aspects are treated as separate problems linked in a sequential procedure. As evaluation scenario, parameter estimation of a Gaussian puff model based on measurements gathered by a team of sensor-carrying UAVs is considered. An optimum design criterion is minimized subject to a UAV's linearized motion dynamics model to determine a sequence of spatiotemporal waypoints where measurements are most valuable for improving the parameter estimate. The waypoints serve as input for a model-predictive controller that is based on a mixed-integer linear program (MILP) formulation of the overall system [4]. This formulation can be extended to additional cooperative mission goals, e.g. visiting specified patrol checkpoints [5] or forming a communication bridge.

The full decentralization of the proposed solution and its modular ROS implementation make it flexible and scalable with respect to type and number of the involved UAVs, and further increase its computational efficiency towards online application on board of each UAV.

References

[1] D. Uciński, *Optimal Measurement Methods for Distributed Parameter System Identification*. Boca Raton: CRC Press, 2005.

[2] C. Tricaud, "Optimal Sensing and Actuation Policies for Networked Mobile Agents in a Class of Cyber-Physical Systems," Ph.D. dissertation, 2010.

[3] J. Haugen and L. Imsland, "Monitoring an Advection-Diffusion Process Using Aerial Mobile Sensors," *Unmanned Systems*, vol. 3, no. 3, pp. 221–238, 2015.

[4] J. Kuhn, C. Reinl, and O. von Stryk, "Predictive Control for Multi-Robot Observation of Multiple Moving Targets Based on Discrete-Continuous Linear Models," in *Proceedings of the 18th IFAC World Congress*, 2011.

[5] J. Euler and O. von Stryk, "Decentralized Data-Driven Control of Cooperating Sensor Carrying Vehicles in a Multi-Objective Monitoring Scenario," in *55th IEEE Conference on Decision and Control (submitted)*, 2016.

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Combining Gaze Stabilization Reflexes for Humanoid Robots

Markus Grotz, David Sippel and Tamim Asfour

***Abstract*— Walking on uneven terrains is one of the challenging tasks for humanoid robots. Walking, being prone to external disturbances also affects the head position where cameras are usually mounted leading to blurred scene images and changing field of view during locomotion. However, stable camera images are of utmost importance for object detection and next-step planning. Without gaze stabilization, such tasks cannot be performed properly. We tackle this issue by combining various human inspired reflexes in order to stabilize a desired view target. The implementation is fully integrated in our robot software framework ArmarX and and the approach has been evaluated in simulation w.r.t. perception and execution tasks.**

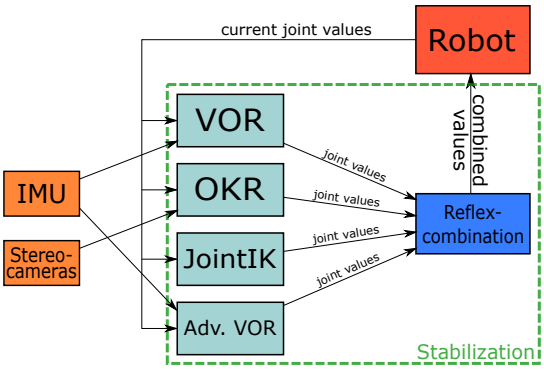

Fig. 1. Combination of different reflex for gaze stabilization. The sensors rely on different sensor input data. Resulting compensatory joint values are weighted based on the current task.

I. Motivation and Problem Definition

Bipedal locomotion for humanoid robots requires accurate knowledge of the environment. Here, an increased awareness of the environment can facilitate next step planning and further improve the robot's agility. Humans fuse inertial and visual information for a stable view in order to manoeuvre through cluttered environments. The vestibulo-ocular reflex (VOR), for example, generates eye movements to compensate head movements and enables us to focus on point of interests. In addition, the optokinetic reflex (OKR) relies on visual information to minimizing the optical flow in the current image. For robots, the goal is to generate compensatory joint commands in order to minimize head motions. Our approach is to combine human inspired reflexes to provide stable camera images and support vision-based components .

II. Related Work

Gay et al. [1] address the issue of self-induced motions by using a Hopf Adaptive Frequency Oscillator to compensate motions based on the optical flow. Their approach tries to predict future head motions by learning the parameters for the oscillators. However, due to the design the approach is limited to periodic movements (sine wave like).

Roncone et al. [2] propose an integrated gaze stabilization system for humanoid robots. Their system includes two reflexes to reduce the velocity of a fixation point. One feedback and one feed-forward component. The first on is based on IMU data (c.f. human VOR) while the latter is based on motor commands (IK reflex). The feedback component is used to compensate the translational velocity of the fixation point and feed-forward component considers the own movements of the robot to reduce the rotational velocity of the fixation point.

III. Own Approach and Contribution

We propose to combine the multiple reflexes since each individual approach is appropriate for a different task. Figure III shows the interaction between the various reflexes. Depending on the current task the weights of the computed joint values are adapted. For instance, during locomotion the Joint IK reflex is more dominant and able to reduce the self induced motions by the robot. For grasping tasks the head position is usually not affect and an activation of the Joint IK reflex would introduce noise. Our experiments show that a combination of the reflexes leads to an improved compensatory head movements w.r.t. to the optical flow.

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References

[1] S. Gay, A. Ijspeert, and J. Santos Victor, "Predictive gaze stabilization during periodic locomotion based on adaptive frequency oscillators," in *2012 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 271–278.

[2] A. Roncone, U. Pattacini, G. Metta, and L. Natale, "Gaze stabilization for humanoid robots: A comprehensive framework," in *2014 IEEE-RAS 14th International Conference on Humanoid Robots (Humanoids 2014)*, pp. 259–264.

Single Camera Based Multiple Pedestrian Tracking for Resource-Limited Hardware Systems

Tanittha Sutjaritvorakul[1], Songlin Piao[1] and Karsten Berns[1]

Abstract— **Multiple Pedestrian Tracking becomes commonly embedded in Advanced Driver Assistance Systems (ADAS) and self-driving car. Tracking can minimize the discontinuous problem in detection via data association. Despite the effort to reduce an accident rate, the tracking remains the challenging problem. In particular, it is time-critical and requires high computing tasks. Our goal is to formulate a compact and fast tracking system in order to yield reasonable accuracy and low computation cost. In other words, we aim to replace the computationally heavy filtering framework with simple feature-based tracker. It can be therefore installed in mobile commercial vehicles e.g. heavy-duty or agricultural vehicles.**

I. Motivation and Problem Definition

Pedestrian detection is one of the key points in vehicle safety technologies. Unfortunately, the detection is not precise along the time. Tracking surrounding pedestrians with a single camera helps to increase the detection rate, so that the number of pedestrian fatalities and injuries could be reduced. But in a real world scenario, pedestrian tracking from a vehicle is still a troublesome problem because of a potentially moving camera and noise, unpredictable appearance and movement, clutters, occlusions and abrupt changes in the scene. In addition, the automotive application limits to load the vehicle with resource-limited hardware systems unlike high performance desktop PCs or GPGPU. The system is accordingly a compact CPU based board coupled with on-board FPGA processing.

II. Related Work

Tracking-by-detection approaches, like [1], become widely used to handle those tracking difficulties. They mainly consist of two tasks which are object detection and association. Object detection is to recognize and assign objects into a certain class while the association is to link noisy object detections on a new image frame based on previously tracked objects. Despite only detecting human with a camera from the significant developments, like HOG[2] or DPM[3], the detection response remains inaccurate. As a result, this possibly misdirects the object association between detections and tracked results. Although a probabilistic-based tracking framework e.g., particle filters[4], returns good tracking result using sampling methods, the computation cost is very high. Alternatively the classic linear model in Kalman filter is faster yet with possibly low detection rate. Unlike the filtering framework, Kalal *et al*.[5] explicitly decomposed a long-term feature-based tracking task into tracking, learning and detection parts. Tracking failures could be detected automatically through estimating forward-backward errors[6].

III. Own Approach and Contribution

Considering aforementioned problems, our approach and contribution present as follows. Instead of the computationally heavy Bayesian based filter[4], Median Flow tracker, the quite accurate and low computational feature-based tracker integrating with a tracking error correction[6], is used as our primary tracking algorithm. Besides solving online computing capability on low specification hardware, we formulate two-layer hierarchical tracking framework in order to cope with the unreliable detection or the discontinuous problem. The tracking target status is defined to represent internal state transition i.e. *stable*, *unstable_active* and *unstable_inactive*. The tracking state of each target keeps changing between these two layers. At the end, we assessed our framework on a standard dataset by comparing detection and tracking performance with other state-of-art methods.

Acknowledgment

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References

[1] M. Breitenstein, F. Reichlin, B. Leibe, E. Koller-Meier, and L. Van Gool, "Robust tracking-by-detection using a detector confidence particle filter," in *Computer Vision, 2009 IEEE 12th International Conference on*, 29 2009-oct. 2 2009, pp. 1515 –1522.

[2] N. Dalal and B. Triggs, "Histograms of oriented gradients for human detection," in *International Conference on Computer Vision & Pattern Recognition*, C. Schmid, S. Soatto, and C. Tomasi, Eds., vol. 2, INRIA Rhône-Alpes, ZIRST-655, av. de l'Europe, Montbonnot-38334, June 2005, pp. 886–893.

[3] P. F. Felzenszwalb, R. B. Girshick, D. McAllester, and D. Ramanan, "Object detection with discriminatively trained part-based models," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 32, no. 9, pp. 1627–1645, Sept. 2010.

[4] W. Choi, C. Pantofaru, and S. Savarese, "A general framework for tracking multiple people from a moving camera," *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, vol. 35, no. 7, pp. 1577–1591, July 2013.

[5] Z. Kalal, K. Mikolajczyk, and J. Matas, "Tracking-learning-detection," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 34, no. 7, pp. 1409–1422, July 2012.

[6] ——, "Forward-backward error: Automatic detection of tracking failures," in *Pattern Recognition (ICPR), 2010 20th International Conference on*, aug. 2010, pp. 2756 –2759.

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Whole-Body Sensory Concept for Compliant Mobile Robots

Marina Kollmitz Andreas Wachaja Tobias Schubert Wolfram Burgard

***Abstract*— Most of the conventional approaches to mobile robot navigation avoid any kind of contact with the environment or with humans. In crowded environments, however, this strict constraint might prevent the robot from making any progress towards the goal, because the remaining space is too narrow. Furthermore, direct physical contact can be used as a means of intuitive communication between a robot and humans. We present a whole-body sensory concept based on one 6 DoF force-torque sensor to detect interaction forces on the robot body. By enabling the robot to feel the impact of a physical interaction, we soften the no-collision constraint and allow new human-robot interaction concepts for mobile robots.**

I. Motivation and Problem Definition

Robots increasingly share their workspaces with humans, which requires new concepts for human safety. The close proximity also allows for intuitive and efficient physical interaction between humans and robots. Two possible interaction scenarios are depicted in Fig. 1. The left image of this figure depicts a robot that gently pushes a person to pass through a crowd of people, while in the right image, the person pushes the robot out of her desired path. Both interactions require the robot to feel the contact with its environment.

II. Related Work

Haddadin *et al.* [1] presented a concept for human safety in shared workspaces for robot manipulators. For mobile robots, Hirata *et al.* [2] proposed an approach to cooperative object transportation where a human pushes the robot along a pre-planned path, indicating the desired robot velocity. Similar to us, they used a 6 DoF force-torque sensor between the robot base and the body to measure interaction forces, but they do not evaluate the exact impact location of the force. Kim *et al.* [3] evaluated the interaction forces on the robot body with torque sensors in the robot's drive train, but the approach requires a precise model of various physical properties, such as wheel friction and motor torque. In contrast, we use a single, high-precision sensor to measure the interaction forces and torques, independent of the drive train properties.

III. Own Approach and Contribution

We present a whole-body sensory concept that enables the robot to detect forces on the entire robot body. Our robot uses one high-precision 6 DoF force-torque sensor, as visualized in Fig. 2. One side of the force-torque sensor is attached to the omnidirectional robot base, the other is attached to the robot shell. Thus, the force-torque sensor can measure forces and torques between both robot parts.

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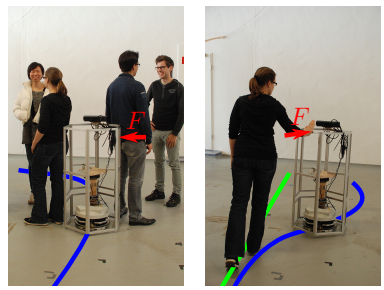

Fig. 1: Envisioned physical interaction scenarios with humans

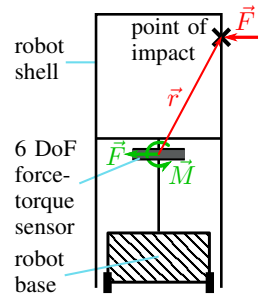

Fig. 2: Whole-body sensory concept

For an impact force $\vec{F}$ on the robot body at a lever arm $\vec{r}$ (Fig. 2), the force-torque sensor measures the same force $\vec{F}$ and a torque $\vec{M}$:

$$\vec{M} = \vec{r} \times \vec{F} \tag{1}$$

$$\vec{M} = \hat{F}\vec{r} \quad \text{with} \quad \hat{F} = \begin{pmatrix} 0 & F_z & -F_y \\ -F_z & 0 & F_x \\ F_y & -F_x & 0 \end{pmatrix} \tag{2}$$

To find the point of impact of the force $\vec{F}$, we need to calculate $\vec{r}$ from the measured $\vec{F}$ and $\vec{M}$. However, $\hat{F}$ is singular, therefore Eq. (2) cannot be solved directly for $\vec{r}$. Instead, all possible solutions for $\vec{r}$ lie on a straight line in the 3D space. We calculate the point of impact, using the shape of the robot body and assuming that the impact force results from pushing the robot instead of pulling. Knowing the location of the force in addition to the direction enables us to distinguish different types of physical contact and to design novel interaction concepts for mobile robots.

References

[1] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, "Requirements for safe robots: measurements, analysis and new insights," *The Int. Journal of Robotics Research*, vol. 28, no. 11-12, 2009.

[2] Y. Hirata, T. Takagi, K. Kosuge, H. Asama, H. Kaetsu, and K. Kawabata, "Map-based control of distributed robot helpers for transporting an object in cooperation with a human," in *IEEE Int. Conf. on Robotics and Automation (ICRA)*, vol. 3, 2001.

[3] K. S. Kim, T. Llado, and L. Sentis, "Full-body collision detection and reaction with omnidirectional mobile platforms: a step towards safe human-robot interaction," *Autonomous Robots*, vol. 40, no. 2, 2016.

System identification of a feed-forward controlled robotic leg to mimic human running gaits

Christian Schumacher[1], Heiko Schlarb[2] and André Seyfarth[1],

***Abstract*— In this study we present the results of a system identification method of a feed-forward controlled robotic leg to mimic human running for shoe testing. In order to realize a realistic running motion, a *Design of Experiment (DOE)* with a 24 full fractional *Plackett Burman design (L24)* is performed. Results are analysed to identify key control parameters and their influence on system dynamics.**

I. Motivation and Problem Definition

Human testing of shoe prototype requires a lot of resources (subjects, equipment). Here, reproducible motions performed by a robotic system allow for more efficient testing.

II. Related Work

Previous shoe testing machines [1] apply artificial loads. An other approach is to mimic running gaits by a robotic test machine, they mostly use a compliant hip and a springy leg [2], [3]. In order to describe the roll-over motion of the foot we use a stationary robotic leg (Fig. 1) designed and manufactured by TETRA Ilmenau GmbH.

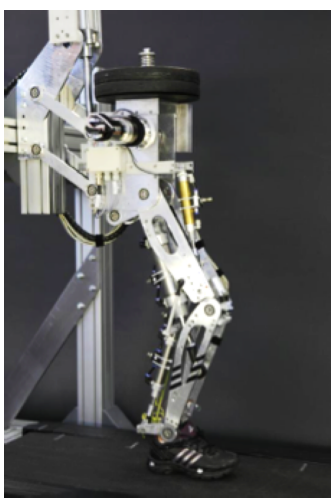

Fig. 1. Design of the one-legged shoe testing machine.

III. Own Approach and Contribution

For the system identification 23 control parameters (e.g. valve timings, treadmill speed etc.) and specific quality criteria of the running motion (amount and timing of ground-reaction-force (GRF) peak) were chosen. A full fractional design by *Plackett Burman* (*L24*) with two levels is used to scan the main dependencies. 24 experiments were conducted, all with different parameter settings. A 2D build-in force sensor (proximal of the ankle joint) and angle encoders captured GRF and joint angles. The measured vertical GRF of the 24 trials and its mean curve can be seen in Fig. 2.

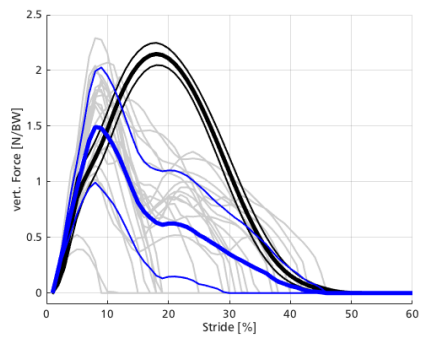

Fig. 2. Mean and S.D. vertical GRF over multiple strides, human running reference data (black) and robot leg data (mean: blue, trials: grey).

Although some parameter settings resulted in similar GRF peak values compared to the reference data [4], most tested parameter settings resulted in deviations especially during late stance. GRF peaks are almost 10% [Stride] earlier than the reference. Key control parameters are identified by comparing its effects on the motion quality criteria (e.g. GRF peak, Fig. 3). Based on these results, hardware adaptations for possible improvements can be derived.

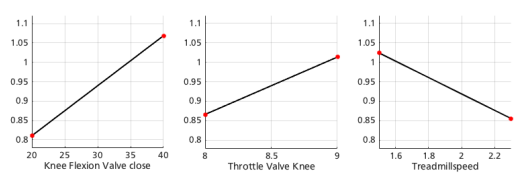

Fig. 3. Effect diagram of key control parameters, control parameters with greater slopes have higher influence on the GRF peak.

References

[1] S. Odenwald, "Test methods in the development of sports equipment," in *The Engineering of Sport 6*. Springer, 2006, pp. 301–306.
[2] M. H. Raibert, *Legged robots that balance*, 1986.
[3] M. Ahmadi and M. Buehler, "The arl monopod ii running robot: Control and energetics," in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, vol. 3. IEEE, 1999, pp. 1689–1694.
[4] S. Lipfert, "Kinematic and dynamic similarities between walking and running, hamburg: Verlag dr," *Kovac, ISBN-10: 3830050305*, 2010.

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Interactive Perception for Autonomous Robotic Manipulation

Roberto Martín-Martín[1] and Oliver Brock[2]

Abstract— **Many of the properties a robot needs to perceive to manipulate explain how the environment reacts to certain actions. To perceive these properties the robot has to interact and understand the changes in the sensor signals as consequences of the interactions. In my thesis we propose a framework to interpret changes in multi-modal continuous sensor streams using priors about their correlation to purposeful robot actions. The framework can be applied to ongoing interactions and close the loop to support robot manipulation.**

Keywords: Perception, Manipulation, Recursive Estimation.

I. Motivation and Problem Definition

Perception for manipulation differs from traditional computer vision approaches in two important ways. First, perception must reveal not only information about the environment itself but also information about the effect the robot can have on the environment. The understanding of how a robot can affect the world enables purposeful and goal-directed action. Second, the robot can support its own perception by interacting with the world. This reveals novel information or makes available information more reliable and robust. The revealed information must be quickly available to support and monitor ongoing robot interactions.

II. Related Work

The origins of interactive perception can be rooted in active perception [1], [2]. This ground-breaking paradigm in computer vision exploited known correlations between changes in the parameters of the sensor and in sensor signals. Active perception converted ill-posed perceptual problems into well-posed. A natural progression in robotics was to use the interaction capabilities of the robot in a similar manner. Interactive perception [3], [4] includes interactions as part of the perceptual process and exploits known correlations between actions and the reaction of the environment. Interactive perception has been successfully applied to object segmentation, classification and recognition, kinematic structure estimation and pile clearing [5], [6], [7]. However, these methods lack to fully exploit the known correlations between action and changes in sensor signals and to make the perceived information available to support the interaction.

III. Own Approach and Contribution

In this thesis, we investigate and develop a comprehensive understanding of multi-modal interactive perception and translate this understanding into a working real-world perception/manipulation system. Our starting point is the view that perception extracts task-relevant information from a very high-dimensional sensor stream. This extraction must be realized in a highly efficient manner so as to enable real-time perceptual feedback during manipulation. We take recursive Bayesian estimation to be the core of our algorithmic approach. This approach enables us to leverage available prior knowledge in the interpretation of sensor data. By formulating appropriate task-specific estimation problems and identifying available prior knowledge, we will enable the robust, real-time extraction of task-relevant information from high-dimensional sensor streams. In this view of perception, multiple estimation loops interpret the sensor stream in parallel and mutually serve as additional sources of processed sensor data. Perception now becomes an interconnected network of estimation loops that cooperate to achieve the perceptual task.

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References

[1] J. Aloimonos, I. Weiss, and A. Bandyopadhyay, "Active vision," *International Journal of Computer Vision*, vol. 1, no. 4, pp. 333–356, 1988.
[2] R. Bajcsy, "Active perception," *Proceedings of the IEEE*, vol. 76, no. 8, pp. 966 –1005, Aug. 1988.
[3] P. M. Fitzpatrick and G. Metta, "Towards manipulation-driven vision," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 1. IEEE, 2002, pp. 43–48.
[4] D. Katz and O. Brock, "Interactive Perception: Closing the Gap Between Action and Perception," in *IEEE International Conference on Robotics and Automotion (ICRA). Workshop: From features to actions-Unifying perspectives in computational and robot vision*, 2007.
[5] D. Schiebener, A. Ude, and T. Asfour, "Physical interaction for segmentation of unknown textured and non-textured rigid objects," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 0–0.
[6] K. Hausman, F. Balint-Benczedi, D. Pangercic, Z.-C. Marton, R. Ueda, K. Okada, and M. Beetz, "Tracking-based interactive segmentation of textureless objects," in *Proceedings of the IEEE International Conference on Robotics and Automotion (ICRA)*, 2013, pp. 1122–1129.
[7] J. Sturm, C. Stachniss, V. Pradeep, C. Plagemann, K. Konolige, and W. Burgard, "Learning Kinematic Models for Articulated Objects," in *Proceedings of the International Joint Conference on Artificial Intelligence*, 2009.

Learning Convolutional Filters for Tactile Manipulation

Martin Meier[1], Robert Haschke[1] and Helge J. Ritter[1]

***Abstract*— We present a machine learning approach to distinguish between different contact states during robotic manipulation tasks based on tactile sensors. By utilizing deep learning techniques with tactile sensor data, we are able to increase classification accuracy in stable vs. slip classification tasks and are even able to subdivide the "slip" condition into translational and rotational slip. In another experiment, considering indirect contact detection (when pushing an object against a wall), we were able to increase the contact detection rate by ≈12% when using convolutional networks compared to a standard multilayer perceptron with a single hidden layer.**

Keywords: haptic-based manipulation, deep learning

I. Introduction

Enabling robots to execute fine manipulations tasks, for example assembling parts or using tools, requires not only rich motor skills but also comprehensive sensing abilities. Keeping track of the used tool or part with vision-based methods is only possible to some extend – due to strong occlusions and limited spatial resolution. One possibility to acquire continuous and reliable contact state information during manipulation tasks is to equip the manipulator with tactile sensors. To extract the current contact state from tactile sensor data – for example to know whether the object is stable or starts slipping – two major possibilities exist. Either using an analytical approach by measuring friction properties of all objects involved in the manipulation task and then creating a detailed contact model based on the friction properties and sensor readings, or by employing machine learning techniques to distinguish between different contact states.

II. Related Work

The work presented in [1] followed the modeling approach and measured the friction coefficient between a test object and a tactile sensor. With the measured friction coefficient, the author was able to successfully detect slip events when the force exerted from the sensor to the test object was decreased. The authors in [2] used a multi layer perceptron (MLP) to classify stable vs. slipping conditions and were able to detect the onset of slippage even before it was detected by an inertial measurement unit.

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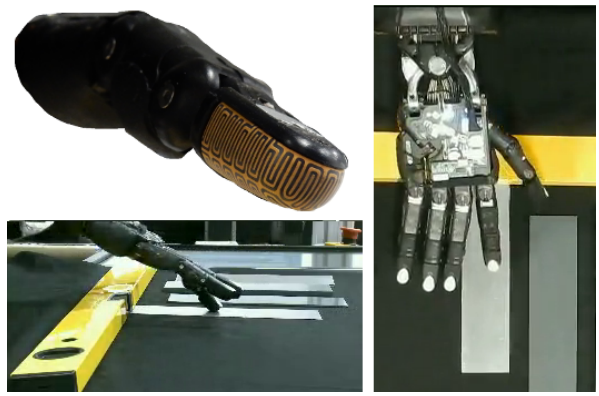

Fig. 1. Top left: Finger of a Shadow Robot Hand equipped with a tactile sensor. Bottom left and right: Tactile manipulation of light objects. Contact between the pushed aluminum plate and the yellow bar is detected through slip classification with a convolutional network.

III. Own Approach and Contribution

We evaluated convolutional networks in different tasks with two kinds of piezo-resistive sensors. In the first task, we used two planar sensors with an array of 16×16 taxels [3] to discriminate between a stable state, rotational and translational slip. The data was preprocessed by applying a short time Fourier transformation on the time series for each taxel to obtain a frequency representation (64 frames recorded at 1kHz). By using two convolutional and pooling layers as well as a final, fully connected layer, we achieved classification accuracies of nearly 98%.

In another task, we used a Shadow Robot Hand equipped with similar piezo-resistive sensors in the fingertips to push a light object against a fixed obstacle as shown in Fig. 1. The goal here was to detect the contact between object and obstacle by the state transition of the finger from "sliding with" the object to "slipping over" it. By using two small convolutional layers and the same preprocessing, we were able to increase the classification accuracy from 72% to 81% compared to a standard MLP.

Using deeper architectures proved to be beneficial when analyzing tactile data in different tasks and could be a building block for more advanced manipulation tasks.

References

[1] C. Melchiorri, "Slip detection and control using tactile and force sensors," *Trans. on Mechatronics*, vol. 5, no. 3, pp. 235–243, 2000.

[2] Z. Su, K. Hausman, Y. Chebotar, A. Molchanov, G. E. Loeb, G. S. Sukhatme, and S. Schaal, "Force estimation and slip detection/classification for grip control using a biomimetic tactile sensor," in *Proc. Humanoids*, 2015, pp. 297–303.

[3] C. Schürmann, R. Koiva, R. Haschke, and H. Ritter, "A modular high-speed tactile sensor for human manipulation research," in *World Haptics Conference (WHC)*, 2011, pp. 339–344.

Cognition-Guided Surgery - Context-aware assistance in the operating room of the future

S. Speidel[1], S. Bodenstedt[1], A. Bihlmaier[1], D. Katic[1], J. Hutzl[1], M. Wagner[2], H. Kenngott[2], B. Müller-Stich[2], H. Wörn[1], R. Dillmann[1]

***Abstract*— With advances in computer- and robotic-assisted surgery, there is an increasing amount of valuable data which can be used to improve patient therapy. Although a lot of information is available, this is an overwhelming challenge for physicians and leads to distractions, especially in the operation room. We propose a context-aware assistance system which acts as an automatic information filter and avoids information overflow. The system analyses multimodal intraoperative sensor data, performs a knowledge-based interpretation and generates assistance depending on the operation phase.**

I. Motivation and Problem Definition

With advances in computer- and robotic-assisted surgery, there is an increasing amount of valuable data which can be used intraoperatively to help surgeons treat patients and improve outcome. Although a lot of data is available, complex assistance systems, information overload and poor integration into the surgical workflow are overwhelming challenges for surgeons in the operating room (OR). The vision of the SFB/Transregio 125 Cognition-Guided Surgery is a Cognitive Surgical Assistant CoSA, a technical-cognitive system which thinks along the lines of a human assistant and gains experience while supporting the surgeon. For the first time it is possible to generate a context-aware assistance in the OR of the future, which avoids information overflow, provides semi-autonomous robotic assistance and adapts to the current needs of the surgeon.

II. Related Work

Recently, research into surgical context-awareness has been gaining more and more interest. The approaches can be distinguished by the types of signals used to recognize the operation phase [1], [2] as well as the interpretation method and formalization to represent surgeries[3], [4], [5].

III. Own Approach and Contribution

In this talk a context-aware assistance system for laparoscopic surgery in the context of the SFB/Transregio 125 is presented. The system analyses multimodal intraoperative sensor data [6] and performs a knowledge-based interpretation [7]. Depending on the OR context an assistance is generated, e.g. a robot-assisted semi-autonomous camera guidance which learns from surgical experience [8], image-based quantitative measurements of organs [9] as well as the visualization of risk and target structures [10]. Such systems provide new man-machine interaction techniques in the OR of the future and could help to improve patient therapy.

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References

[1] O. Dergachyova, D. Bouget, A. Huaulm, X. Morandi, and P. Jannin, "Automatic data-driven real-time segmentation and recognition of surgical workflow," *Int J CARS*, 2016.

[2] A. Twinanda, S. Shehata, D. Mutter, J. Marescaux, M. de Mathelin, and N. Padoy, "Endonet: A deep architecture for recognition tasks on laparoscopic videos," arXiv preprint arXiv:1602.03012, 2016.

[3] F. Lalys and P. Jannin, "Surgical process modelling: a review," *Int J CARS*, 2014.

[4] D. Neumuth, F. Loebe, H. Herre, and T. Neumuth, "Modeling surgical processes: a four-level translational approach," *Artif Intell Med*, 2011.

[5] R. Stauder, A. Okur, L. Peter, A. Schneider, M. Kranzfelder, H. Feussner, and N. Navab, "Random forests for phase detection in surgical workflow analysis," in *IPCAI*, 2014.

[6] S. Bodenstedt, J. Grtler, M. Wagner, H. Kenngott, B. Mller-Stich, R. Dillmann, and S. Speidel, "Superpixel-based structure classification for laparoscopic surgery," in *SPIE Medical Imaging*, 2016.

[7] D. Katic, J. Schuck, A. Wekerle, H. Kenngott, B. Mller-Stich, R. Dillmann, and S. Speidel, "Bridging the gap between formal and experience-based knowledge for context-aware laparoscopy," *Int J CARS*, 2016.

[8] A. Bihlmaier, S. Bodenstedt, S. Speidel, P. Nicolai, H. Wrn, M. Wagner, P. Mietkowski, B. Mller-Stich, and H. Kenngott, "A learning camera robot for laparoscopic surgery," in *Hamyln Symposium*, 2015.

[9] S. Bodenstedt, M. Wagner, B. Mayer, K. Stemmer, H. Kenngott, B. Mueller-Stich, R. Dillmann, and S. Speidel, "Image-based laparoscopic bowel measurement," *Int J CARS*, 2015.

[10] D. Katic, A. Wekerle, J. Grtler, P. Spengler, S. Bodenstedt, S. Rhl, S. Suwelack, H. Kenngott, M. Wagner, B. Mller-Stich, R. Dillmann, and S. Speidel, "Context-aware augmented reality in laparoscopic surgery," *Comp. Med. Imag. and Graph.*, vol. 37, no. 2, pp. 174–182, 2013.

Development of Compliant Hyper-redundant Mechanisms for Robotic Catheters and Analysis of Controllability

Pedro Rodriguez Nasdar[1,3], Pinar Boyraz[2,3], Tobias Ortmaier[3], Annika Raatz[3]

***Abstract*— In this work, three different modules are designed to build compliant hyper-redundant mechanisms, used as back-bone of robotic catheters. The current technology and approach includes co-centric, pre-shaped tubular structures or cable-driven piece-wise controlled catheters. Although both of these approaches are successful, there is still room for improvement if a novel approach including the compliant hyper-redundant mechanisms is taken. Unlike the tubular co-centric or cable-driven continuum/p.w. continuum structures, segment-based precise control of the structure can be achieved in both shape and stiffness control at local or global scale. In this study, we compare 3 modules based on their kinematics and variable-stiffness capability. Finally, we assess the controllability of the modules based on their structure and identify the trade-offs between shape-control and stiffness-control in navigations tasks, for example torturous vein passages especially in cardio-vascular operations.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

The main idea of a hyper-redundant robotic platform with a modular building block is to increase the controllability and maneuverability of the robotic catheters. Increasing the number of DoF seems to be the main advantage, however it is surpassed by the fully continuous robot (i.e. tubular/telescopic pre-curved continuum robots) that can be manipulated in 3D space without the need of lengthy inverse-kinematic calculations. Although fully-continuous robotic platforms have this advantage, for most cases, segment-based local-control is very difficult to obtain and despite the inherent compliancy, the stiffness control for most continuous robots is not possible. Therefore in this work, we propose three different modular hyper-redundant robotic designs that can offer segment-based position control as well as adjustable stiffness. When the robotic catheter has both the position and the stiffness control, the navigation of the robotic catheter inside torturous channels becomes an optimal control problem, where the position and force are controlled with varying priorities according to the path-planning and task. This greatly increases the safety of the robotic catheter. In this work, novel hyper-redundant modules are introduced and compared using kinematics and stiffness analysis.

II. Related Work

One of the first robots helping surgeons in OR and performing some part of the operation is the DaVinci system, which has been already commercialized[1]. However, there is still need to develop versatile minimally invasive surgical robots with which the operations involving difficult-to-reach places can be safely performed. These types of surgical robots usually have a form of continuum or hyper-redundant structure and are remotely driven to navigate inside narrow and torturous channels[2]. The recently proposed hyper-redundant modular structures still use rigid or semi-rigid backbones or general frames[3],[4], [5]. The cable driven structures are light-weight and compact, however have a limitation due to cable friction and inter-dependency between the sections .

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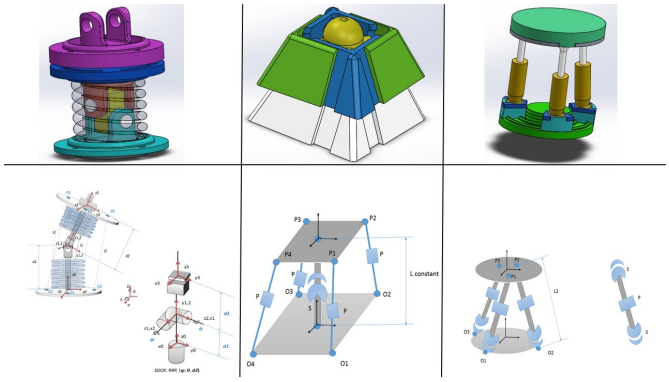

Fig. 1. Three modules and their kinematic structures.

III. Own Approach and Contribution

In this work, a systematical approach is taken to improve the design of hyper-redundant and modular robotic structures by emphasizing the functional properties such as independent module/segment control, variable-adjustable stiffness. The proposed designs are aimed at improving both position and force controllability. For this purpose, three modular structures are designed with at least three DoF each, allowing light-weight actuators to be embedded for segment control. In addition, variable stiffness at least for one axis is assured.The first one is a hybrid module (HM) with two parallel plates supported by a middle shaft featuring a universal-joint to obtain pan-tilt movement and having a compression spring around.The second module is inspired by nature and the previous studies on sea-horse-tail[6]. This module has a passive spherical joint in the middle and overlapping corner parts. The SHT has lateral and oblique muscles moving the exoskeleton of the seahorse. Using a similar approach, the SHT-module can contract and expand radially while the individual segments are able to perform rotations in 3D. Although the mechanism has no structural compliancy axially, it can have a great radial compliancy. Finally, the third module is a PKM with 3x SPS struts that can be reconfigured in a curvilinear manner.The module benefits from the compact and stable PKM while allowing the stiffness to be adjusted. The actuation units are located in prismatic joints and curvilinear adjustments. In terms of controllability, we find SHT and 3xSPS mechanisms more controllable due to the over-actuated structure and reduced uncertainty with the exclusion of the spring.

References

[1] M. Schardt,J.M. Naids,M.R. Knouse, et.al., "DaVinci Robot Assisted Sub-Retinal Injection,"*Investigative Ophthalmology and Visual Science*, vol. 56, no. 7,pp.364, 2015.

[2] B.A. Jones,R.J. Webster, "Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review," *The International Journal of Robotics Research*, vol. 29, iss.no. 13, pp.1661–1683, 2010.

[3] M.M. Tonapi,I.S. Godage,A.M. Vijaykumar,I.D. Walker, "A novel continuum robotic cable aimed at applications in space," *Advanced Robotics*, vol. 29, no. 6, pp. 861–875, 2015.

[4] Z. Li,H. Ren,P.W.Y. Chiu,R. Du,H. Yu, "A novel constrained wire-driven flexible mechanism and ist kinematic analysis," *Mechanism and Machine Theory*, vol. 95, no. 3, pp. 59–75, 2016.

[5] O. Salomon,A. Wolf,"Inclined links hyper-redundant elephant-trunk-like robot," *Jrnl of Mechanics and Robotics*, vol. 4, pp. 045001–1-6, 2012.

[6] M.M. Porter,D. Adriaens,R.L. Hatton, et.al"Why the seahorse tail is square?," *Biomechanics*, vol. 349,iss.6243, pp. 46–53, 2015.

METABot - Magnetic Extensible Tendon Actuated Continuum Robot

Ernar Amanov, Thien-Dang Nguyen, and Jessica Burgner-Kahrs

***Abstract*— Continuum manipulators possess the ability to move along nonlinear paths and avoid obstacles in confined environments. However, existing designs have some inherent restrictions: limited range of curvatures or fixed segment lengths. Hence, to achieve motion along a tortuous path in a confined environment in a follow-the-leader manner requires thoughtful a priori design parameter selection. As a result, follow-the-leader motion is only achievable for a limited number of cases. Here, we present a novel miniaturized (7 mm diameter) tendon-driven manipulator design with extensible segments (METABot) enabling follow-the-leader movement.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

Continuum robots are composed of one (or more) elastic continua leading to increased dexterity and manipulability. Diverse continuum manipulator designs have been proposed thus far [1]. However, these robot designs cannot necessarily deploy along a path in a follow-the-leader motion. This is highly desirable as the majority of applications for continuum robots involve confined and tortuous workspaces.

II. Related work

While concentric tube continuum robots can vary the length of a segment during actuation, the precurvature of each component tube and the elastic interaction between the tubes determines the range of achievable curvatures. On the other hand, tendon-driven manipulators enable a larger variety of curvatures for each segment, but the length of each segment is fixed such that deployment can only be achieved through linear translation of the whole manipulator. Fluidic or pneumatic actuated continuum manipulators allow for limited extension/contraction of the manipulator ($\approx$30 %). For those manipulators, follow-the-leader motion along a specific tortuous path requires a custom choice of segment lengths and curvature ranges. Recently, concurrent developments led to novel continuum manipulator designs with inherent follow-the-leader motion capabilities ([2] and [3]).

III. Own Approach and Contribution

In this paper, we present our recent advancements for our magnetic extensible tendon-driven continuum robot (METABot) design [3]. While we previously presented promising follow-the-leader simulation results [4], we now performed initial experiments on the METABot prototype.

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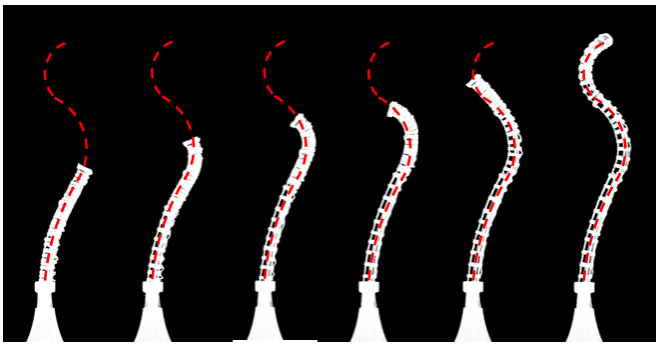

Fig. 1: Follow-the-leader deployment along a desired path (dashed red line).

We adopt our previous design [3] and expand it to 3 segments. Each segment bends and extends/contracts independently resulting in 9 DOF for the whole manipulator. Each segment can vary its length between 15-70 mm.

The spacer disks were further reduced in diameter (now 7 mm) and are equipped with permanent magnets (Neodymium) to ensure equidistant distribution during extension/contraction. The backbone is composed of 3 telescoping, straight, and superelastic NiTi tubes. To achieve independent actuation we use 12 DC motors with encoders (Maxon Motor AG, Switzerland), 9 for tendon actuation and 3 for the segment extension/contraction. The motors are controlled by a motion controller (DCM4040/DCM4080, Galil Motion Control, CA, USA).

In order to evaluate the follow-the-leader behavior qualitatively, we chose a random path with three constant curvature sections and taught in ten intermediate configurations along this path. Fig. 1 shows photographs taken from the motion sequence. We can observe, that the manipulator deploys well along the desired path (dashed red line) with slight deviations on the transition from one curvature to the next. The results are promising and we are currently in the process of conducting quantitative experiments.

References

[1] J. Burgner-Kahrs, D. C. Rucker, and H. Choset, "Continuum Robots for Medical Applications: A Survey," *IEEE Transactions on Robotics*, vol. 31, no. 6, pp. 1261–1280, 2015.

[2] B. Kang, R. Kojcev, and E. Sinibaldi, "The First Interlaced Continuum Robot, Devised to Intrinsically Follow the Leader," *Plos One*, vol. 11, no. 2, 2016.

[3] T.-D. Nguyen and J. Burgner-Kahrs, "A Tendon-Driven Continuum Robot with Extensible Sections," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2015, pp. 2130–2135.

[4] M. Neumann and J. Burgner-Kahrs, "Considerations for Follow-the-Leader Motion of Extensible Tendon-driven Continuum Robots," in *IEEE International Conference on Robotics and Automation (in press)*, 2016.

Real-time 4D Object Modelling for Adaptive Manipulation

Seongyong Koo and Sven Behnke

***Abstract*— Adaptive manipulation is a matter of modelling object that can be applicable to general objects and refinable into a given specific target. This paper addresses an issue of constructing 4D object model (temporally associated 3D spatial representation) in real-time. We propose an efficient incremental learning method to update the 4D model from a sequence of temporal difference of prediction and measurements.**

I. Motivation and Problem Definition

Adaptability is a key feature to success for robots manipulating unseen objects in a new space. Many vision-guided manipulators relying on a predefined object model need to estimate model parameters beforehand, which restricts adaptability to the degree of model expressiveness. Model-free approach, so called end-to-end learning, does not have such limitations, but it usually needs much time to obtain sufficient visual and motor data to overcome over-fitting issue to the given tasks.

An efficient way is to reuse the initially constructed models, upon which a manipulation skill is defined, and adapt the models to the given new object. In this paper, we aims to propose a new flexible object representation and efficient learning mechanism to adapt a predefined manipulation skill in real-time.

II. Related Work

With the assumption that manipulation skills can be defined on the target object model, adaptability of manipulation can be improved in the related two functionalities, eye-hand coordination and object recognition.

To achieve adaptive eye-hand coordination instead of estimating fixed camera manipulator models, the kinematic dependency of a camera to current robot configuration should be estimated at running time. Levine et al. [1] achieved the task specific hand-eye coordination with deep learning and large-scale data collection. Koo and Behnke [2] proposed an online learning approach to estimate virtual camera pose that best matches self-observation of robot arm to visual measurements by employing CAD model data of robot manipulator.

In order to manipulate new objects, pose of unknown objects and grasping location should be identified. Pinto and Gupta [3] proposed a model-free strategy to detect grasping locations of unseen objects using deep learning with self data collection and supervision. Koo et al. [4] proposed an efficient incremental learning method to segment and track multiple unknown objects in real-time with a flexible spatio-temporal 3D object model.

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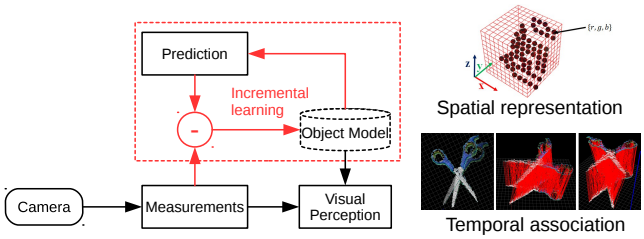

Fig. 1. Incremental learning process to construct 4D object model

III. Own Approach and Contribution

We extend our incremental approach to construct 3D object model in previous work [2], [4] by incorporating deep 3D shape representation as in [5]. The key issue for adaptation is real-time update of the model from the measurements given new object. In the proposed architecture as shown in Fig. 1, the object model can be incrementally updated at every time step by comparing object shape predicted from the previously constructed model and new measurements. The comparison is performed by using 2 channel 3D Convolutional Neural Network (CNN) models, which outputs a distance matrix of 3D voxel pairs. The temporal difference information constructs temporal association of parts in the model, resulting in 4D model of an object. With the constructed 4D model, a pre-trained object model can be adapted to the new measurements in an online manner. It enables to estimate an accurate object pose and infer manipulation data for any given articulated object.

References

[1] S. Levine, P. Pastor, A. Krizhevsky, and D. Quillen, "Learning hand-eye coordination for robotic grasping with deep learning and large-scale data collection," *arXiv preprint arXiv:1603.02199*, 2016.

[2] S. Koo and S. Behnke, "Focused online visual-motor coordination for a dual-arm robot manipulator," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2016, pp. 1580–1586.

[3] L. Pinto and A. Gupta, "Supersizing self-supervision: Learning to grasp from 50k tries and 700 robot hours," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2016, pp. 3407–3413.

[4] S. Koo, D. Lee, and D.-S. Kwon, "Incremental object learning and robust tracking of multiple objects from rgb-d point set data," *Journal of Visual Communication and Image Representation*, vol. 25, no. 1, pp. 108–121, 2014.

[5] Z. Wu, S. Song, A. Khosla, F. Yu, L. Zhang, X. Tang, and J. Xiao, "3d shapenets: A deep representation for volumetric shapes," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2015, pp. 1912–1920.

Rapid Motion Planning for Intracerebral Hemorrhage Evacuation using a Tubular Aspiration Robot

Josephine Granna, Yannick Vornehm, Carolin Fellmann, and Jessica Burgner-Kahrs

***Abstract*— Intracerebral hemorrhage evacuation using a tubular aspiration robot enables minimally-invasive surgery. To suction out blood from within, a 3D motion plan has to be determined prior to evacuation as well as intraoperatively based on CT images. In this paper, our previously proposed 3D motion planner is extended by a new objective, such that it allows for minimization of traveled distance in configuration space or traveled Cartesian distance of the tubular aspiration robot.**

I. Motivation and Problem Definition

Intracerebral hemorrhages appear, when a blood vessel ruptures within the brain and blood accumulates. They are life-threatening as they induce pressure onto surrounding brain structures. A surgical removal requires the opening of the skull (craniotomy) and is often not beneficial for the patient, as additional disruption of healthy brain tissue during the procedure cannot be prevented in order to gain access to the hemorrhage [1].

II. Related Work

To reduce the invasiveness, researchers proposed robotic surgery using a tendon driven continuum robot [2] or a tubular aspiration robot [3] to perform intracerebral hemorrhage evacuation. The tubular aspiration robot performs the evacuation in a minimally-invasive manner autonomously. We previously introduced a 3D motion planner [4] which maximizes coverage while minimizing traveled distance in configuration space.

III. Own Approach and Contribution

In this paper, we extend our algorithm by a new objective: traveled Cartesian distance and evaluate the results by comparing the overall traveled distance in Cartesian and configuration space for 3 patient datasets.

The tubular aspiration robot (Fig. 1 top) is composed of two tubes: the outer being straight to reach the hemorrhage on a straight path and the inner being precurved, which articulates within the hemorrhage to suction out the blood. Configuration parameters are the translation of both tubes β_1, β_2 and the rotation of the inner tube α. Our 3D motion planner starts at the center of the volume and considers spherical intervals s around it, moving from one interval to another, while moving with least cost within these intervals.

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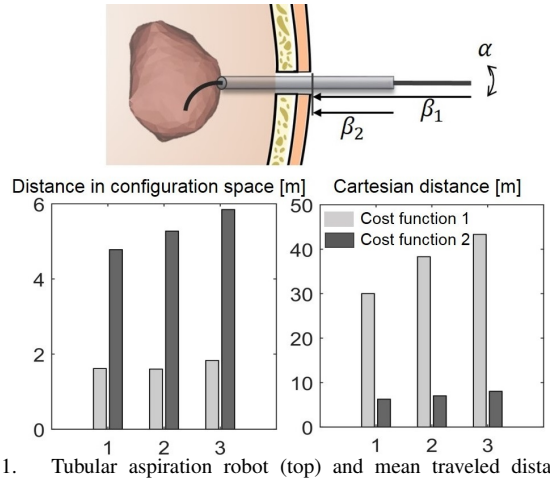


Fig. 1. Tubular aspiration robot (top) and mean traveled distance in configuration and Cartesian space for 3 patient datasets (bottom).

We defined the cost for traveling from one configuration to another by considering the least change in configuration parameters (cost function 1). Here, we propose a new cost function, where the robot travels with least Cartesian distance from one end-effector position to the next (cost function 2). For evaluation, we computed the 3D motion plan for 3 example patient hemorrhages using a randomly chosen entry path into each hemorrhage volume and computed the overall distance traveled in configuration and Cartesian space.

IV. Results

We ran the algorithm on an Intel Core i7-4790 3.60 GHz implemented in C++. The mean computation time for one patient dataset was 0.42 s. The interval size was chosen empirically as 2 mm. Fig. 1 (botttom) illustrates, that each cost function successfully resulted in either low traveled distance in configuration space or Cartesian distance for each patient case. In future work, we will experimentally validate the effectiveness of both cost functions.

References

[1] C. J. van Asch, M. J. Luitse, G. J. Rinkel, I. van der Tweel, A. Algra, and C. J. Klijn, "Incidence, case fatality, and functional outcome of intracerebral haemorrhage over time, according to age, sex, and ethnic origin: a systematic review and meta-analysis," *The Lancet Neurology*, vol. 9, no. 2, pp. 167–176, 2010.

[2] W. Zhao and J. P. Desai, "Towards the development of a new tendon-driven minimally invasive neurosurgical intracranial robot," in *ASME 2014 Dynamic Systems and Control Conference*, 2014, pp. 795–797.

[3] J. Burgner, P. J. Swaney, R. A. Lathrop, K. D. Weaver, and R. J. Webster, "Debulking from within: A robotic steerable cannula for intracerebral hemorrhage evacuation," *IEEE Transactions on Biomedical Engineering*, vol. 60, no. 9, pp. 2567–2575, 2013.

[4] J. Granna, I. S. Godage, R. Wirz, K. D. Weaver, R. J. Webster, and J. Burgner-Kahrs, "A 3-D Volume Coverage Path Planning Algorithm With Application to Intracerebral Hemorrhage Evacuation," *IEEE Robotics and Automation Letters*, vol. 1, no. 2, pp. 876–883, 2016.

Optimal Control of Lifting Motions for Spinal Exoskeleton Design

Paul Manns[1] and Katja Mombaur[1]

***Abstract*— Lower back pain is a major cause of sick leave days of workers in many fields. The responsible motions often cannot be avoided which motivates the development of supporting exoskeletons. However, only few projects and few literature on spinal exoskeletons exists, and there are no established design rules. We are developing computational methods to close this gap. We apply optimal control methods to compute the best possible support during motions imposing risks to the lumbar spine. Our simulations include the human model together with a parameterized exoskeleton.**

Spinal exoskeletons, optimal control of human motions

I. Motivation and Problem Definition

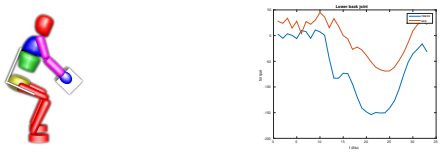
Workers from various fields have to perform tasks that endanger their lumbar spine. Consequently, lower back pain is a frequent problem for many professions. The H2020 project SPEXOR aims to address this problem by developing a spinal exoskeleton prototype for lower back pain prevention, rehabilitation and vocational reintegration. The exact requirements and the best possible design of a spinal exoskeleton to support risky tasks in these working situations are still unknown. Within the project, we develop computational methods to simulate and analyze these risky motions. Optimal control problems (OCPs) based on multibody system models of humans and exoskeletons are our means to predict motions and loads. Furthermore, design parameters of the exoskeleton can be optimized as part of the OCP.

II. Related Work

Several projects exist in the field of lower limb exoskeletons, such as the Berkeley Lower Extremity Exoskeleton (BLEEX) [1] that supports walking with increased payload. Commercially available platforms include the Ekso [2]. There are also newer research prototypes of lower limb exoskeletons such as the KIT-Exo [3]. Only few exoskeletons for the spinal region exist. The project RoboMate develops a back-supporting exoskeleton for manual working tasks. The Laevo [4] is a commercial passive platforms to support bending and lifting motions. No systematic simulation and design optimization has been performed to develop those spinal exoskeletons.

III. Own Approach and Contribution

In our research, we develop computational models and optimization approaches to predict typical human movements that endanger the lower spine and optimize the design of exoskeletons supporting such motions. We implement a 2D human model similar, see fig. 1a. For dynamic multibody system modeling, we use the code RBDL [5] that implements the Articulated Body Algorithm (ABA). In a first set of computations, a passive exoskeleton with a leaf spring that is attached at the upper trunk and the pelvis of the human model. We simulate a motion consisting of a bending down phase and a lifting phase in which a box-shaped object is lifted by the human while minimizing the squared torques and a head stabilization term. We solve the multi-phase OCPs with the direct multiple shooting implementation MUSCOD [6]. Fig. 1b shows the torque profiles acting at the lower back for bending and lifting of 25 kg with and without exoskeleton. The exoskeleton reduces the load on the lower back joint significantly.



(a) Human model when picking up the box-shaped object.

(b) Lower back torque profile with (orange) and without (blue) exoskeleton.

Fig. 1: Planar lifting model and lower back torque profile

Acknowledgment

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References

[1] A. B. Zoss, H. Kazerooni, and A. Chu, "Biomechanical design of the berkeley lower extremity exoskeleton (bleex)," *Mechatronics, IEEE/ASME Transactions on*, vol. 11, no. 2, pp. 128–138, 2006.

[2] S. A. Kolakowsky-Hayner, J. Crew, S. Moran, and A. Shah, "Safety and feasibility of using the eksotm bionic exoskeleton to aid ambulation after spinal cord injury," *Journal of Spine*, vol. 2013, 2013.

[3] J. Beil, G. Perner, and T. Asfour, "Design and control of the lower limb exoskeleton kit-exo-1," in *Rehabilitation Robotics (ICORR), 2015 IEEE International Conference on*. IEEE, 2015, pp. 119–124.

[4] T. Bosch, J. van Eck, K. Knitel, and M. de Looze, "The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work," *Applied Ergonomics*, vol. 54, pp. 212–217, 2016.

[5] M. Felis, "Rbdl – the rigid body dynamics library (2011)."

[6] D. B. Leineweber, I. Bauer, H. G. Bock, and J. P. Schlöder, "An efficient multiple shooting based reduced sqp strategy for large-scale dynamic process optimization. part 1: theoretical aspects," *Computers & Chemical Engineering*, vol. 27, no. 2, pp. 157–166, 2003.

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Robot Learns to Use Tactile Tool Interacting with Unknown Object

Qiang Li, Robert Haschke and Helge Ritter

***Abstract*— We propose a contact-based manipulation strategy to learn the kinematic model of a grasped tool, using tactile sensing delivered through a tactile matrix sensor covering the tool surface. The learned tool parameters are integrated into a robot kinematics model to update the manipulation kinematics chain, thereby realizing a step towards a "plastic body schema" for flexible tool use by a robot. We demonstrate the feasibility of the method with a tactile servoing experiment in which the tactile tool is employed as the end-effector to interact with surfaces about which the robot has no detailed geometry and physics information.**

I. Motivation and Problem Definition

Recent research findings in neuroscience highlight how the high plasticity of our body schema supports rapid and easy learning of dexterous tool manipulation. This project seeks to realize a similarly plastic body schema for a robot to bring tool use learning closer to human performance.

In order to make this ambitious goal feasible, we define a number of simpler subtasks, and start from learning to manipulate a single tactile tool shown in Fig. 1 left. The task is that robot exploits the available kinematics model (without tool), safely exploring the tool interaction with the predominant external object geometry primitives: corner, edge or surface. The tool kinematics parameters are rapidly learned combining active exploration behaviors and tactile feedback.

II. Related Work

In [1], we have proposed a very flexible tactile servoing control framework to support robot interaction with surfaces in the absence of detailed knowledge about geometrical and physical properties. In that work, we assembled a planar tactile matrix sensor on the robot end-effector (EEF) and assumed that the transformation between the robot EEF frame and the tactile sensor frame was known. The present work drops this assumption and focuses on learning the transformation. [2] proposed to use a force-torque sensor to calibrate the grasped tool and focused on the point-surface contact case. They deliberately designed a force and motion trajectory and impedance controller in order to obtain sample data for a convergent estimation of the tool parameters.

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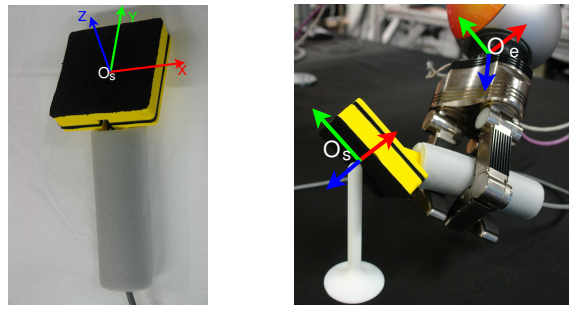

Fig. 1: Tactile tool with contact frame (left) and manipulation scenario (right)

III. Own Approach and Contribution

The main contribution of this paper is the safe contact-based controller mechanism and exploration strategy to learn the tactile tool kinematics (homogeneous matrix T_e^s). Because the tool kinematics is unknown, we can not use the robot kinematics theory to control the grasped tool moving in the Cartesian space. However exploiting the flexible tactile servo framework, it is possible to safely slide slide/tool on the object surface if the tool normal direction is given. Concretely we define the desired contact force between the tactile tool and object, sensor frame O_s's reactive translational movement to maintain the contact can be computed from the deviation of the contact force and the estimated normal direction. This movement is then used to calculate the desired velocity of robot end-effector O_e, which is implemented according to the known robot arm kinematics.

The whole learning process is divided into three stages.

1) the normal direction of the tactile tool frame O_s' is coarsely estimated from the approach direction when a human guides the tactile tool towards the object. This manual guidance will be replaced by vision-based approaches in the future.
2) Robot slides the tool on the object. Using tactile trajectory on the sensor to estimate the rotation matrix between the tangent surface of the sensor frame and the generated tangent surface from the estimated normal direction.
3) Robot rolls its EEF O_e around x, y axis. Using the tactile trajectory and the estimated rolling twist to estimate the translation from O_e to O_s.

References

[1] Q. Li, C. Schürmann, R. Haschke, and H. J. Ritter, "A control framework for tactile servoing." in *Robotics: Science and systems*, 2013.

[2] Y. Karayiannidis, C. Smith, F. E. Vina, and D. Kragic, "Online contact point estimation for uncalibrated tool use," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*. IEEE, 2014, pp. 2488–2494.

Decentralized Dynamic Data-Driven Monitoring and Estimation of Contaminant Plumes

Tobias Ritter[1,*], Stefan Ulbrich[2], and Oskar von Stryk[1]

***Abstract*— Applying robotic systems in context of online monitoring and estimation of contaminant plumes has turned out to be very advantageous. The robotic vehicles are equipped with sensors whose measurements are used to repeatedly update the predictions of a partial differential equation (PDE) model of the considered physical process. Based on the resulting estimates of process state and parameters, the trajectories of the robots are adapted to obtain more informative measurements at other promising locations. While most of the related approaches require a central supercomputer, a novel decentralized approach that combines the benefits of distributed approaches with the prediction ability of PDE process models has been developed.**

I. Motivation and Problem Definition

Air pollution due to accidental releases of chemical substances might have critical impacts on human health and well-being. Therefore, monitoring of contaminant plumes caused by accidental chemical leaks is an important task for disaster response. State variables, source location and further important process parameters have to be estimated repeatedly and online. For this purpose, robotic systems are equipped with sensors and their measurements are directly combined with predictions of a model to update the current estimates. Moreover, based on the estimates, the sensor vehicles can be driven to locations where measurements seem to be more profitable. To avoid a central point of failure, to consider limited communication range and bandwidth and to attain scalability, it appears to be desirable to design a decentralized monitoring approach, i.e. an approach in which every sensor processes local information on-board and exchanges this information with its neighbors. On the other side, the use of a PDE-model, which is able to provide physically accurate forecasts, but whose solution is usually very expensive should be considered. Thus, the challenge is to develop a PDE-based monitoring strategy that fits the reduced computational on-board power and the limited communication ranges.

II. Related Work

While a large number of publications in context of dynamic data-driven approaches for atmospheric dispersion monitoring focuses on centralized approaches [1], [2], work related to decentralized approaches is limited [3], [4]. Furthermore, models used in decentralized approaches are very simple. Discretized PDEs describing the physics of the underlying process are not considered.

III. Own Approach and Contribution

A decentralized dynamic data-driven application system for plume estimation that is based on the forecasts of a discretized PDE-model has been developed [5]. To meet the computational requirements, estimation problem and vehicle controller are considered separate parts [6], [7]. Furthermore, Proper Orthogonal Decomposition is used to generate Reduced Order Models. Every sensor node maintains such a reduced model and incorporates its own measurements using the Kalman Filter. Estimates are exchanged between neighboring sensors and Covariance Intersection is used to fuse the data. New profitable measurement locations are identified based on probable source locations and the uncertainty of the estimates. A vehicle controller that is based on a Mixed Integer Linear Program formulation of the problem is in charge of guiding the sensor vehicles to these locations using a Model Predictive Control approach.

References

[1] Z. Song, Y. Chen, J. Liang, and D. Ucinski, "Optimal mobile sensor motion planning under nonholonomic constraints for parameter estimation of distributed systems," *International Journal of Intelligent Systems Technologies and Applications*, vol. 3, no. 3/4, pp. 277–295, 2007.

[2] L. Peng, M. Silic, and K. Mohseni, "A DDDAS plume monitoring system with reduced Kalman Filter," in *Proc. of the International Conference on Computational Science (ICCS)*. Elsevier, 2015, pp. 2533–2542.

[3] M. Duckham, S. Nittel, and M. Worboys, "Monitoring dynamic spatial fields using responsive geosensor networks," in *Proc. of the 13th Annual ACM International Workshop on Geographic Information Systems*, 2005, pp. 51–60.

[4] R. Stranders, A. Farinelli, A. Rogers, and N. Jennings, "Decentralised coordination of mobile sensors using the max-sum algorithm," in *Proc. of the 21st International Joint Conference on Artificial Intelligence*, 2009, pp. 299–304.

[5] T. Ritter, J. Euler, S. Ulbrich, and O. von Stryk, "Decentralized dynamic data-driven monitoring of atmospheric dispersion processes," in *Proc. of the International Conference on Computational Science (ICCS)*. Elsevier, 2016, pp. 919–930.

[6] J. Euler, T. Ritter, S. Ulbrich, and O. von Stryk, "Centralized ensemble-based trajectory planning of cooperating sensors for estimating atmospheric dispersion processes," in *Dynamic Data-Driven Environmental Systems Science*, ser. Lecture Notes in Computer Science. Springer International Publishing, 2015, no. 8964, pp. 322–333.

[7] T. Ritter, J. Euler, S. Ulbrich, and O. von Stryk, "Adaptive observation strategy for dispersion process estimation using cooperating mobile sensors," in *Proc. of the 19th IFAC World Congress*, 2014, pp. 5302 – 5308.

[1]Tobias Ritter and Oskar von Stryk are with Graduate School Computational Engineering and with Simulation, Systems Optimization and Robotics Group, Department of Computer Science, Technische Universität Darmstadt {ritter,stryk}@sim.tu-darmstadt.de

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Target Prediction in an Immersive Pick-and-Place Scenario

Dennis Krupke[1], Frank Steinicke[2] and Jianwei Zhang[3]

***Abstract*— Current developments in the area of user interface (UI) technologies, as well as robotic systems, provide enormous potential to reshape the future of human-robot interaction (HRI) and collaboration. However, the design of reliable, intuitive and comfortable user interfaces is a challenging task. In this work, we try to apply techniques from virtual reality (VR) research to a high-level robot control task, such as pick-and-place of objects. Systems with shared autonomy provide larger flexibility in application and purpose but need additional methods for interaction between human and robot. In this work we try to fill the gap between the operator and the robotic system with intuitive control methods by utilizing a head-mounted display (HMD).**

Keywords: virtual reality, pick-and-place, prediction

I. Background

As the original occurrence of human-robot interaction, teleoperation has made significant advances in robotics in the last decades of research. By incorporating predicting components, it is possible to integrate the human more seamlessly than in the classical role of an operator [1]. Predicting human behavior in order to prepare and execute an appropriate response of the robot in time is essential and has to be solved before we can bring robots in our everyday life efficiently. VR seems to be promising when working on a remote site since VR representations of 3D scenarios like in a typical pick-and-place task are easier to understand than normal screen representations [2]. Prediction of user input in direct selection tasks represented in VR face the lack of appropriate modeling of user behavior. This is caused by several perceptional differences to currently established models and methods [3].

Most predictive systems are based on the extraction of the motion direction of user input and a computational model of the users' motion time during input phase [4]. The motion time computation is based on the original formulation of Fitts' law for 1D input [5]. In many publications reformulations and extensions for 2D, 3D, moving targets and many more are presented. For VR applications with HMDs, there is still room for improvements when predicting movement time in direct selection tasks. Some work on Teleoperation of robots with ROS and VR already exists [6]. But the implementation of a shared autonomy based interface using VR technology is hard to find.

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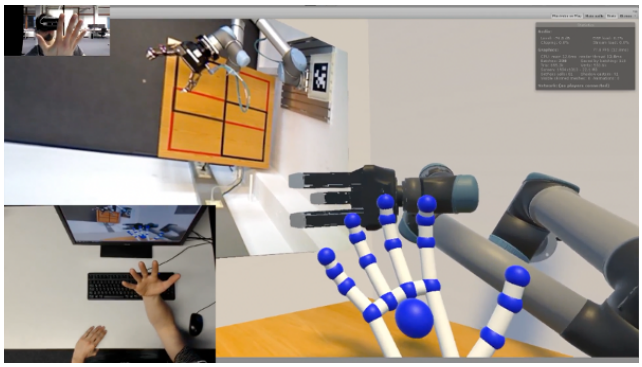
II. Approach

UR-5, Robotiq 3-finger adaptive gripper, and sensors like a Kinect are controlled by ROS nodes. The user interface, which is optionally at a distant location, is implemented with Unity3D, featuring high-quality immersive 3D visualizations. For communication via the network ROS messages are serialized to JSON strings and vice versa. Direct control of the gripper by mid-air gestures of the operator's hand is already implemented as a proof of concept.

Future work will incorporate a reformulation of a prediction model and the implementation of a shared autonomy based control for pick-and-place tasks. In a user study speed-profiles of hand motions during selection of objects will be recorded and analyzed. As a result, a more precise model for the index of difficulty in selection tasks in an HMD/VR scenario will be developed. Further improvements of the predictor are achievable by integrating gaze tracking into a crossmodal interaction system. The resulting user interface system will be capable of minimizing or compensating network and communication latency of the system.



References

[1] N. Roy, P. Newman, and S. Srinivasa, *Formalizing Assistive Teleoperation*. MIT Press, 2013, p. 504.

[2] G. Burdea, "Invited review: the synergy between virtual reality and robotics," *Robotics and Automation, IEEE Transactions on*, vol. 15, no. 3, pp. 400–410, Jun 1999.

[3] C.-P. Kuan and K.-Y. Young, "Challenges in vr-based robot teleoperation," in *Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on*, vol. 3, Sept 2003, pp. 4392–4397 vol.3.

[4] E. Lank, Y.-C. N. Cheng, and J. Ruiz, "Endpoint prediction using motion kinematics," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '07. New York, NY, USA: ACM, 2007, pp. 637–646.

[5] P. M. Fitts, "The information capacity of the human motor system in controlling the amplitude of movement," *Journal of Experimental PSychology*, vol. 74, pp. 381–391, 1954.

[6] L. Peppoloni, F. Brizzi, C. Avizzano, and E. Ruffaldi, "Immersive ros-integrated framework for robot teleoperation," in *3D User Interfaces (3DUI), 2015 IEEE Symposium on*, March 2015, pp. 177–178.

Probabilistic Camera Localization from Images using Text Spotting

Noha Radwan Gian Diego Tipaldi Luciano Spinello Wolfram Burgard

***Abstract*— Text is one of the richest sources of information in an urban environment. Although textual information is heavily relied on by humans for a majority of the daily tasks, its usage has not been completely exploited in the field of robotics. In this work, we propose a localization approach utilizing textual features in urban environments. Starting at an unknown location, equipped with an RGB-camera and a compass, our approach uses off-the-shelf text extraction methods to identify text labels in the vicinity. We then apply a probabilistic localization approach with specific sensor models to integrate multiple observations. An extensive evaluation with real-world data gathered in different cities reveals a 40% improvement over GPS-based localization when using our method.**

I. Motivation and Problem Definition

Localization is one of the fundamental problems in the area of mobile robotics. The accurate knowledge of the robot position enables a variety of tasks including navigation, transportation, as well as search and rescue. In outdoor settings, GPS is a popular solution to estimate the position of the robot or the user. Although GPS can theoretically reach an accuracy of a few meters, it cannot always be achieved in practice; due to GPS outages, e.g. inside or near buildings. In the classical approach, localization is performed after a previous visit of the environment during which a map has been built. The advantage of leveraging and processing publicly available maps lies in the ability to localize without an initial mapping step. The majority of currently available methods mostly focus on only one kind of information provided by those maps, namely geo-tagged street-level imagery.

In this paper, we propose an approach that uses a standard RGB camera to localize on publicly available online maps *without* any use of street-level imagery. The idea is to exploit the rich textual meta-data content of maps, such as the annotations of local shops and businesses as high-level information. Our approach moves away from visual-based feature matching to use mid-level representations for estimating the current geo-location of an image. Specifically, we concentrate on extracting text "in the wild" from images that are cross-referenced from the available annotated map. This enables a new localization form that has global-scale breadth, low bandwidth requirements (no images are transferred in the network) and, lifelong capabilities (users and companies continually update their maps).

II. Related Work

Approaches to solve the localization problem can be divided into two groups: topological approaches, and metric approaches. Topological approaches aim at obtaining an estimate of the current position with respect to some known structures in the environment, while metric localization methods typically estimate the position of the robot with respect to geographic coordinates. Metric localization approaches can be further split into two subcategories: direct image matching-based techniques, and retrieval-based techniques (refer to Sattler et al. for a comparison [2]).

Human-readable text has also been exploited in the context of computer vision and robotics. Both, Tsai et al. [4] and Schroth et al. [3], extract text and visual features from query images. They perform feature matching to return the best corresponding images from a database such that both the query image and the retrieved images contain the same textual information. Posner et al. use extracted text from natural scene images to return images that are semantically relevant to a query [1]. They build a generative model to create connections between extracted text and locations in a map. To the best of our knowledge, we are the first to exploit textual information in natural scenes for localization purposes.

III. Own Approach and Contribution

In this work, we consider the following problem: given that we are standing at a certain position, equipped with an RGB-camera and a compass, can we accurately localize ourselves using surrounding textual information? The answer is yes, given a map of the environment, and at least two text-containing images. Our approach works by extracting textual features from the images and associating them to landmarks in the environment. To obtain a robust estimate of our pose, we adapt Monte Carlo methods accounting for the employed text extraction approach. In extensive experiments we evaluate the performance of the approach, and the results demonstrate an accuracy of up to 1 meter, which corresponds to a 40% improvement over GPS poses obtained with a mobile device.

All authors are with the University of Freiburg, Institute of Computer Science, 79110, Germany. This work has been partially supported by the European Commission under the grant number FP7-610603-EUROPA2.

References

[1] I. Posner, P. Corke, and P. Newman. Using text-spotting to query the world. In *Int. Conf. on Intelligent Robots and Systems (IROS)*, pages 3181–3186, 2010.

[2] T. Sattler, T. Weyand, B. Leibe, and L. Kobbelt. Image retrieval for image-based localization revisited. In *British Machine Vision Conference (BMVC)*, volume 6, page 7, 2012.

[3] G. Schroth, S. Hilsenbeck, R. Huitl, F. Schweiger, and E. Steinbach. Exploiting text-related features for content-based image retrieval. In *Int. Symposium on Multimedia (ISM)*, pages 77–84, 2011.

[4] S. S. Tsai, H. Chen, D. M. Chen, and B. Girod. Mobile visual search with word-HOG descriptors. In *Data Compression Conference (DCC)*, pages 343–352, 2015.

(Inverse) Optimal Control for Matching Higher-Order Moments

Oleg Arenz, Hany Abdulsamad and Gerhard Neumann

***Abstract*— Defining the cost function for optimal control manually is often cumbersome. Instead it is often easier to demonstrate the desired behavior and learn the cost function using inverse optimal control. When aiming to match distributions over features, state of the art methods for inverse optimal control often suffer dramatically as they are not designed for matching higher order moments. We therefore present a new approach for inverse optimal control that is tailored for matching distributions by minimizing the relative entropy to a distribution over features. This distribution could be either estimated based on expert demonstrations for inverse optimal control, or defined manually for optimal control.**

I. Motivation and Problem Definition

Optimal control computes optimal behavior based on a given cost function and the dynamics of the system. However, manually defining a cost function such that the optimal controller solves the desired task is often cumbersome and has to be done by experts.

It is often easier to specify a task by providing desired distributions over features. Such distributions can be either estimated from human demonstration which results in imitation learning, or they can be specified manually. In both cases, better generalizations can be achieved by employing a two-staged approach that first infers a cost function via inverse optimal control and then computes the desired behavior via optimal control.

Many approaches for inverse optimal control are based on matching feature counts in expectation which directly translates to matching the mean of the observed feature distribution. Such methods can also be applied for matching higher-order moments by additionally matching the corresponding products of features in expectation. However, the feature dimension increases significantly in that progress, drastically impairing the performance of the algorithm.

Observing that adding artificial features in that manner looses all information about the relation between the original and the additional features suggests that this class of problems can be solved more efficiently by directly formulating the inverse optimal control problem of matching feature distributions.

II. Related Work

Yin et al. [1] demonstrate robotic handwriting by first solving the inverse optimal control problem via stochastic optimization and afterwards using optimal control to compute the controller. However, their inverse optimal control formulation does not take into account the system dynamics during demonstration and hence the resulting controller does not achieve the desired distribution over trajectories.

Englert et al. 2013 [2] directly learn a controller for matching trajectory distributions by framing imitation learning as a policy search problem. They use the Kullback-Leibler divergence between the induced trajectory distribution of the controller and the target distribution as long-term cost function and optimize it using the model-based policy search algorithm PILCO [3]. However, in contrast to our approach, the optimization is non-convex and computationally heavy.

III. Own Approach and Contribution

Our approach strongly relates to Maximum Entropy Inverse Reinforcement Learning (MaxEnt-IRL) [4], which produces a stochastic controller with maximum entropy while matching the demonstrated feature counts in expectation. However, instead of matching feature counts, we propose to minimize the relative entropy to the demonstrated feature distribution. The corresponding objective of the resulting optimization problem is given by

$$\underset{\pi_t(\mathbf{a}|\mathbf{s})}{\text{maximize}} \sum_{t=1}^{T-1} H(\pi_t(\mathbf{a}|\mathbf{s})) - \sum_{t=2}^{T} \beta_t D_{\mathrm{KL}}\left(p_t(\boldsymbol{\phi})||q_t(\boldsymbol{\phi})\right),$$

where $H(\pi_t(\mathbf{a}|\mathbf{s}))$ denotes the entropy of the controller, β_t is a regularization coefficient trading off the oposing objectives, and $D_{\mathrm{KL}}\left(p_t(\boldsymbol{\phi})||q_t(\boldsymbol{\phi})\right)$ denotes the relative entropy between the feature distribution produced by π, $p_t(\boldsymbol{\phi})$, and the empirical distribution $q_t(\boldsymbol{\phi})$.

Interestingly, solving this optimization problem yields the same gradient as MaxEnt-IRL for $\beta_t \to \infty$, but also yields a closed form estimate of the reward function

$$\tilde{r}_t(\boldsymbol{\phi}) = \beta_t \left(\log q_t(\boldsymbol{\phi} - \log \tilde{p}_t(\boldsymbol{\phi})\right) + \mathit{const}\ ,$$

based on the current estimate of the feature distribution, $\tilde{p}_t(\boldsymbol{\phi})$. Optimization based on this estimate is several thousand times faster than L-BFGS based on the gradient in our preliminary experiments.

References

[1] H. Yin, A. Paiva, and A. Billard, "Learning Cost Function and Trajectory for Robotic Writing Motion," in *14th IEEE-RAS International Conference on Humanoid Robots (Humanoids), 2014*. IEEE, 2014.

[2] P. Englert, A. Paraschos, J. Peters, and M. P. Deisenroth, "Model-based Imitation Learning by Probabilistic Trajectory Matching," in *IEEE International Conference on Robotics and Automation*, 2013.

[3] M. Deisenroth and C. Rasmussen, "PILCO: A Model-Based and Data-Efficient Approach to Policy Search," in *28th International Conference on Machine Learning (ICML)*, 2011.

[4] B. D. Ziebart, J. A. Bagnell, and A. K. Dey, "Modeling Interaction via the Principle of Maximum Causal Entropy," in *Proceedings of the Twenty-seventh International Conference on Machine Learning*, 2010.

Motoric activation of persons with early stage dementia with a robotic system

Denis Štogl[1]

Abstract— **One of the major challenges for our ageing society, is taking care for the elderly, especially if they suffer from cognitive impairments such as dementia. Recent studies show positive effects of physical activation of people with dementia and comparable cognitive impairments. This work presents novel training method for persons suffering from mild cognitive impairment. The training is based on an autonomous robotic system which is used for activation of persons motoric abilities. The evaluation of the gathered data with the proposed system and the initial evaluation of psychological tests show promising results.**

I. Motivation and Problem Definition

In Germany about 1.2 million people are currently suffering from dementia and it is expected as twice as many in 2030 as a consequence of rapid ageing of society. Neuroscientific models of pathological ageing emphasize the loss of cognitive and sensorimotor capacities in the development of maladaptive plastic changes and subsequent cognitive, mental and bodily decline associated with "disuse" of the brain by reduced sensory and motor input. The use of new technologies for training and assistance seems to be a promising approach to at least moderate the progression of the ageing-caused diseases and to support all involved persons (patient, caretakers, doctors, family,..). Goal of this research is to see "how" or "if at all" an robot-based mobile training system could be beneficially used in a therapeutic context for people with mild cognitive impairment (MCI).

II. Related Work

In recent years multiple studies prove positive effects of physical activity for people with dementia and comparable cognitive impairments. Particular valuable sources are meta-studies [1], [2] and studies on healthy persons showing that sensorimotor training aimed at reversing maladaptive plasticity yield significant improvements in key neurocognitive processes that decline with age. Nevertheless no structured training or therapy method is known.

On the technical side, the proposed system is similar to walking assist devices. Current state of research in this field is published in [3] and [4]. Most of the systems use Force-Torque sensors on walker's handles to determinate the navigational intention of the user and some additionally for gait estimation and fall prevention.

For more detailed related work and references see paper describing concept the system [5] and [6] presenting some initial results.

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III. Own Approach and Contribution

The overall goals of this work is to (1) use robotic system in form of walking assist device in therapy for people with MCI and (2) design structured and standardised exercises with measurable progress and outcomes. Until now initial version of training approach and prototype of the system were evaluated in a pilot study with 10 participants (8 male and 2 female) between $66 - 78$ years of age with diagnosed MCI. The medical part of this research was done by "The Central Institute of Mental Health in Mannheim".

The training approach consists of five training sessions, each one hour long. Each session has multiple exercises where the main goal is to control the robotic system along the predefined paths. The exercises are ordered by ascending complexity through the sessions, so that the training begins with a simple exercise like navigating the robot along a straight line, continues with few exercises for controlling robot movements sidewards up to complex exercises, like long parcours with narrow passages (doors) and distrubance forces on particular places unknown to the participants or sidewards navigation of robot with inverted controls.

The training system is based on autonomous mobile platform *rob@work* from *Frauenhofer IPA* with control software implemented in ROS.

The evaluation of the data gathered with mobile platform, like path following precision, MRI data about brain structure and psychological tests (CERAD-Plus and CANTAB) show positive impacts of the herein presented training approach.

References

[1] P. Heyn, B. C. Abreu, and K. J. Ottenbacher, "The effects of exercise training on elderly persons with cognitive impairment and dementia: A meta-analysis1," *Archives of Physical Medicine and Rehabilitation*, vol. 85, no. 10, pp. 1694–1704, 2004.

[2] Bowes Alison, Dawson Alison, Jepson Ruth, and McCabe Louise, "Physical activity for people with dementia: a scoping study," *BMC Geriatr*, vol. 13, no. 1, p. 129, 2013.

[3] C. Dune, P. Gorce, and J. Merlet, "Can smart rollators be used for gait monitoring and fall prevention ?" in *IROS 2012 International Workshop on Assistance and Service Robotics in a Human Environment*, A. Spalazani, D. Daney, O. Simonin, and J. Merlet, Eds., 2012, pp. 59–65.

[4] M. M. Martins, C. P. Santos, A. Frizera-Neto, and R. Ceres, "Assistive mobility devices focusing on Smart Walkers: Classification and review," vol. 60, pp. 548–562, 2012.

[5] D. Stogl, B. Hein, P. Meyer, O. Armbruster, S. Irgenfried, and H. Wörn, "A Technical system for physical activation of persons with mild cognitive impairment," in *Technische Unterstützung für Menschen mit Demenz*, T. Schultz, F. Putze, and A. Kruse, Eds. KIT Scientific Publishing, Karlsruhe, Oct. 2014, pp. 123–143.

[6] O. Armbruster, "Robot-based therapeutic options for persons with early stage dementia," Master's thesis, Karlsruhe Institute of Technology, Oct. 2015.

Proximity Sensors for Safe Human Robot Interaction

Yitao Ding[1]

***Abstract*— In this paper we present our current research in the field of safe human robot interaction by using a new robot skin based on proximity sensing. This new approach allows safe high velocity movements in unknown environments where obstacles like humans may occur compared to impedance and tactile controlled robots. We present the current state of the art in proximity sensors and describe our current work.**

Preferred type of presentation: Oral

I. Motivation and Problem Definition

Considering the fact that today's industrial robots are still very limited in terms of flexibility, safety and human machine interaction, robots can only be used in large fixed production lines. With the development of lightweight and impedance controlled robots basic fundamentals have been introduced for better safety in human machine interaction and for more flexibility in production. Still, robots are only able to react on contact and the robot's movements are following a programmed or taught. Industrial robots equipped with proximity skin allows the use of robotics in changing and unknown environments where the robot can find its path on its own by avoiding obstacles such as humans or other objects. Proximity and distance sensors provide a good solution for the given problem. They are widely used in mobile robotics for obstacle avoidance or SLAM. However, little research is done on using proximity information for obstacle detection and avoidance of industrial robots. Most attempts for workspace observation are 2D/3D-camera based (Visual Servoing) which have occlusion problems hence safety is not guaranteed.

II. Related Work

Related work in proximity based sensing exist in the field of mobile robotics such as autonomous vehicles where usually LIDAR systems are used[1]. In terms of sensor and robotic skin development a lot of work has already been shown by different groups[2]. Nonetheless, most research is done on tactile sensors mounted on fingertips in a limited space configuration or tactile skin with wider surfaces[3]. Development of proximity based skins that covers large parts of the robot are rare but are available[4][5]. Even less work is done regarding proximity servoing[6].

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III. Own Approach and Contribution

Since research on proximity sensors is done by other groups, our main focus is proximity servoing by developing new control algorithms using the sensor data. Most research work on capacitive or optical-reflection based sensor-skins [4], therefore only proximity values can be obtained which depend either on conductivity and grounding or surface reflectance. Without absolute distance values new approaches have to be found in order to control the robot safely. In our current research we implement proximity sensors (Fig. 1) with an absolute detection range from 0 mm to 100 mm. We woll mount the sensor on a Kinova JACO2 robot as test platform for research in control algorithms. Besides of finding suitable distribution and mounting points, we implemented dynamic control and robot parameter identification algorithms which take into account joint torque data to fuse proximity servoing with impedance control.

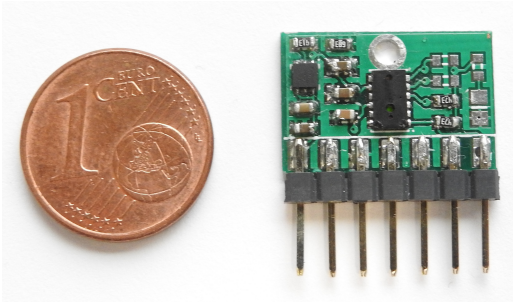


Fig. 1. Distance Sensor

References

[1] P. Wu, S. Xie, H. Liu, J. Luo, and Q. Li, "A novel algorithm of autonomous obstacle-avoidance for mobile robot based on lidar data," in *2015 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, Dec 2015, pp. 2377–2382.

[2] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing 2014 - from humans to humanoids," *IEEE Transactions on Robotics*, vol. 26, no. 1, pp. 1–20, Feb 2010.

[3] Y. Ohmura, Y. Kuniyoshi, and A. Nagakubo, "Conformable and scalable tactile sensor skin for curved surfaces," in *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*, May 2006, pp. 1348–1353.

[4] Stefan Escaida Navarro and Maximiliano Marufo and Yitao Ding and Stephan Puls and Dirk Göger and Björn Hein and Heinz Wörn, "Methods for Safe Human-Robot-Interaction Using Capacitive Tactile Proximity Sensors," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2013, pp. 1149–1154.

[5] P. Mittendorfer and G. Cheng, "Uniform cellular design of artificial robotic skin," in *Robotics; Proceedings of ROBOTIK 2012; 7th German Conference on*, May 2012, pp. 1–5.

[6] Stefan Escaida Navarro and Martin Schonert and Björn Hein and Heinz Wörn, "6D Proximity Servoing for Preshaping and Haptic Exploration Using Capacitive Tactile Proximity Sensors," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2014.

Autonomous Transparent Object Reconstruction

Sven Albrecht[1], Michael Görner*[,2], Joachim Hertzberg[1], Jianwei Zhang[2]

Abstract— **Detecting objects with transparent or highly-reflecting surfaces poses a challenge for active light-based sensors as RGB-D cameras and lidars. Even so, these sensors are often used with robots in mundane indoor-environments where such objects might be encountered. The most successful approaches so far to detect and reconstruct transparent objects either require an explicit training phase for each object type or make assumptions about the objects' shape. This work presents a ROS-based framework to autonomously acquire viewpoint-dependent, 3D reconstructions of transparent objects on top of tables without requiring prior knowledge about their number, shape or size. The necessary RGB-D camera measurements are autonomously collected by the robot and registered using a version of ICP especially suited for tabletop setups.**

Keywords: transparent objects, environment reconstruction, RGB-D perception, point cloud registration

I. Motivation and Problem Definition

Today, many robot setups in indoor-scenarios rely on active light-based sensors as RGB-D cameras or lidars for visual depth-perception. However, these sensors fail to measure the distance to transparent and metallic objects because such materials disperse the light emitted by the sensor. It is important though to detect these "invisible" objects in human environments to check for possible collisions during robotic manipulation, and successful detection is required for everyday household tasks such as setting a table with glasses. Because the measured depth image usually includes characteristic holes of invalid data at the objects' positions, the sensors actually measure a rough 2D contour of these objects instead of their 3D surface. This information can be used to reconstruct the 3D shape of the original object on the basis of observations from multiple perspectives.

II. Related Work

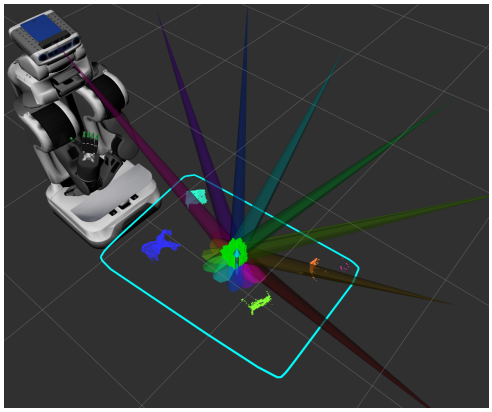
This work aims at the autonomous reconstruction of transparent objects from RGB-D camera data without prior knowledge. Although transparent object reconstruction has been a subject of research for a long time [1], this is still an unsolved problem in most fields. In applied robotics using active light sensors, [2] were the first to propose a detection scheme enabling a robot to grasp drinking glasses. However, they only reconstruct objects from two similar perspectives and assume cylindric shapes. In [3] the authors aimed at the recognition and pose estimation of transparent objects and therefore required a learning phase with opaque versions of the relevant transparent objects. In later work [4] they extended their scheme to object clusters.

III. Own Approach and Contribution

Our approach reconstructs objects on top of a table by intersecting all frusta defined by the camera's respective position and the projection of detected holes in the image onto the plane of the table surface. The robot navigates around the table, focussing on candidate objects, and collects RGB-D camera views of the table surface from different perspectives. Because the relative transformation of the collected views is only roughly approximated by Monte Carlo localization, the views still need to be aligned more accurately. To do so, we propose a version of the ICP algorithm that exploits the table surface detected in each view.

The set of aligned frusta is voxelized into an octomap. Individual objects are extracted as clusters of voxels which where observed from a minimum number of perspectives. Thus, our approach does not require any prior knowledge about the existence, shape, or number of transparent objects it might reconstruct. Even so, the reconstruction is sufficient for collision checking and simple manipulation tasks.

Future work will include the autonomous refinement of the generated models by dexterous manipulation and the recognition of previously observed shapes.



References

[1] I. Ihrke, K. N. Kutulakos, H. P. A. Lensch, M. Magnor, and W. Heidrich, "State of the art in transparent and specular object reconstruction," in *STAR Proc. Eurographics*, 2008, pp. 87–108.

[2] U. Klank, D. Carton, and M. Beetz, "Transparent object detection and reconstruction on a mobile platform," in *Proc. ICRA*, 2011, pp. 5971–5978.

[3] I. Lysenkov, V. Eruhimov, and G. R. Bradski, "Recognition and pose estimation of rigid transparent objects with a Kinect sensor," in *Proc. RSS*, 2012.

[4] I. Lysenkov and V. Rabaud, "Pose estimation of rigid transparent objects in transparent clutter," in *Proc. ICRA*, 2013, pp. 162–169.

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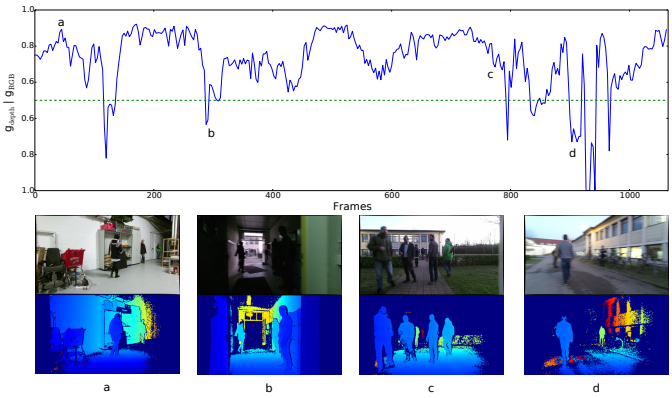
Adaptive Sensor Fusion for RGB-D Object Detection

Oier Mees* Andreas Eitel* Wolfram Burgard

***Abstract*— We propose a novel adaptive fusion approach for object detection that learns weighting the predictions of different sensor modalities in an online manner. We test our method in extensive robot experiments, in which we detect people in a combined indoor and outdoor scenario from RGB-D data, where we show that our method can adapt during harsh dark to bright lighting changes and severe camera motion blur. Our novel adaptive approach is based on a mixture of convolutional neural network (CNN) experts and incorporates multiple modalities including appearance, depth and motion.**

Object detection using different sensors in dynamic environments is challenging, because sensor's noise depends on the environment. On the one hand, in a dark indoor scenario, one would expect the depth information from an RGB-D device to be more reliable than the appearance. On the other hand, the depth stream would not be very informative in a sunny outdoor scenario with distant objects. We show that this kind of "prior" information, can be learned from raw data, without any hand-crafted features and that our fusion approach adapts to the underlying environment without human user intervention. Our contributions are: a) We introduce a novel fusion scheme for object detection, based on a mixture of deep network experts (MoDE), that are fused in an additional gating network. b) We learn the adaptive fusion using a CNN, that is trained to weight the expert classifier outputs, based on high-level features extracted from the expert networks, without the use of "prior" information. c) We evaluate our method in extensive real-world experiments and show that it is more robust in changing environments, than purely vision-based or other multimodal fusion approaches.

Enzweiler *et al.*[1] introduced a mixture of experts approach for people detection using three input modalities, namely appearance, motion and depth. In comparison to our approach the weighting of the experts is constant and therefore not adaptive. Premebida *et al.* [2] trained a late fusion SVM with manually designed features to perform detector fusion from RGB and depth modalities. In comparison, we do not use any prior information to learn the weights for the fusion. Spinello *et al.* [3] proposed a hierarchical mixture of experts approach, where the output of the individual detectors is weighted based on missing information in the sensor modalities. In contrast to their approach, our weighting function is directly learned from a feature representation of the input data. To conclude, most approaches rely on non-adaptive fusion techniques or use manually designed features. None of the reported approaches have tried to perform sensor fusion based on CNN features.



We recorded RGB-D sequences of people from a mobile robot, captured under abrupt changes in lighting conditions, both indoors and outdoors. In comparison to previously recorded datasets for mobile robots, the sequences show the robot driving through poorly illuminated indoor scenes, followed by very bright outdoor scenes in a single experiment. We compare our MoDE fusion approach against averaging the experts and a late fusion approach, where a fully-connected layer is trained on top of the last pooling layer of all network streams. Our novel fusion approach improves the performance by 8.4% AP in comparison to the late fusion approach. Analyzing the output detector trained with MoDE on the test sequence, shows that the average gating weights correlate reasonably well with the respective environment, as can be seen in the Figure. In the bright indoor scenario (sequence: a), the RGB modality is chosen more often, but for example in dark environments (sequence: b) the gating network tends to weight the depth network output higher than the vision-based one. Outdoors (sequence: c), it mainly relies on RGB, especially for the pedestrian at far distance that is almost not visible in the depth image. We also found the depth network to perform better for blurred images (sequence: d). Thus, in the last frames of the test sequence, the RGB outputs are mostly chosen, but for abrupt camera motion the gating network switches with higher frequency.

References

[1] M. Enzweiler and D. M. Gavrila, "A multilevel mixture-of-experts framework for pedestrian classification," *IEEE Transactions on Image Processing*, 2011.

[2] C. Premebida, J. Carreira, J. Batista, and U. Nunes, "Pedestrian detection combining rgb and dense lidar data," in *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, 2014.

[3] L. Spinello and K. O. Arras, "Leveraging RGB-D data: Adaptive fusion and domain adaptation for object detection," in *Proc. of the IEEE Int. Conf. on Robotics & Automation (ICRA)*, 2012.

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