Karlsruher Institut für Technologie

Institut für Regelungs- und Steuerungssysteme
Prof. Dr.-Ing. Sören Hohmann
Wilhelm-Jordan-Weg, Geb. 11.20
76131 Karlsruhe | www.irs.kit.edu

Contact:

Jairo Inga, M.Sc.
jairo.inga@kit.edu

Start: January 2021 **Duration:** 4-6 months

Topics:

State Estimation, Optimization, Cooperative Control, Machine Learning

Abroad Research Internships / Master Theses

Cooperative State Estimation and Control

Description:

A starting research collaboration between the University of Waterloo in Canada and the Institute of Control Systems (IRS) of the KIT is offering research internship positions and master theses in the field of cooperative systems for outstanding master students. The projects have a duration of up 4 to 6 months and take place in Waterloo, Canada. The topics include modeling and identification, optimization and control of cooperative systems for applications in robotics and driving assistance systems.

The research projects are the following:

- **Cooperative State Estimation for Autonomous Mobile Robots**
- **Safe Merging for Automated-Natural Driving Systems**

The positions offer the possibility to experience work in an international research environment, use state-of-the-art test facilities as the University of Waterloo's RoboHub (https://uwaterloo.ca/robohub/), and ultimately to contribute to further advances in automatic control theory. The research projects are supervised by Prof. Ehsan Hashemi of the the University of Waterloo's Department of Mechanical and Mechatronics Engineering. The IRS officially nominates elected students for the application to exchange programs of the University of Waterloo and also supports them in organizational matters.

Further details on the research projects can be found in the next pages.

Requisites:

- Enrollment in the Master program of ETIT or MIT
- Previous experience in modeling and identification, state space methods and optimization, e.g. with the IRS lectures MI, RLM and ODS/ORS
- Proficient English speaking and writing skills

How to apply:

- Prepare a single PDF file which includes
  - a short motivation letter (addressed to Prof. Sören Hohmann)
  - your CV
  - A transcript of records of your bachelor and master studies
  - Other relevant documents of your choice
- All documents must be written in English
- Send the PDF to Jairo Inga (jairo.inga@kit.edu)

Project Proposals for Waterloo-KIT Collaborative Research

Ehsan Hashemi, Prof. William Melek (University of Waterloo–MME), and Prof. Sören Hohman (KIT–IRS)
July 29, 2020

1. **Cooperative State Estimation for Autonomous Mobile Robots**

Overview of Project: Autonomous mobile robots implement simultaneous localization and mapping (SLAM) algorithms and Visual-Inertial Navigation (VIN) solutions to improve navigation and perform various tasks including service, delivery, or manipulation at a target place. Navigation and state estimation approaches are however prone to errors due to complexities in dynamic environment, reliability of visual navigation in presence of dynamic objects, loss of GPS signal, noises in inertial measurement units, and model uncertainties. In this direction, cooperative state estimation is a promising solution to improve reliability by leveraging connectivity between autonomous mobile robots and a base station or infrastructure. Such cooperative approaches have their own challenges due to delay and packet drop in the networked robotic systems, as well as the volume of data transfer. This project aims to develop cooperative (and computationally efficient) state estimation and navigation systems for autonomous mobile robots, in presence of model uncertainties, (such as slips in the dead reckoning approach and dynamic objects) and investigating how machine learning can improve reliability of the cooperative scheme.

Project Specifics and Objectives: This research project aims to develop a reliable cooperative state estimation and navigation system for autonomous mobile robots through connectivity, in a distributed scheme, considering computational constraints as well as wheel slip components in local visual-inertial solutions. The algorithms will be evaluated by existing University of Waterloo RoboHub's *JACKAL* unmanned ground vehicle (UGV) robots equipped with GPS/IMU integrated with ROS (Robot Operating System). The robots will be connected through the long range *LoRa* wireless RF technology.

You will first develop an observer model for visual-inertial navigation and state estimation by using existing visual odometry solutions, robot kinematic/dynamic model, and considering the actuators' bandwidth. (see [1, 2, 3, 4, 5, 6]). Then, you will design a model-based distributed estimator for navigation and augmented perception in a network of two-three *Jackal* mobile robots by using consensus Kalman filter [7, 8, 9]. In order to model uncertainty using a data-driven approach [10] and with the aim of not increasing the local observers' dimensions for large systems, you will study and test how distributed estimation algorithms will be enhanced with machine learning methods. Further challenges are:

- Computational complexities and distributed linear programming might be a challenge for larger networked robotic systems
- Due to communication constraints, you need to investigate what data and with which rate, while maintaining reasonable accuracy, should be transmitted between the robots

More specifically, tasks to achieve the main objectives include: *i)* develop a state observer for visual-inertial navigation (and state estimation) in local agents/robots by using constrained optimization programs and augmenting the observer with the robot dynamic model; *ii)* design a distributed observer, such as distributed Kalman filter, in order to enhance navigation by shared perception, and investigate sufficient conditions for robust filter design using the dissipativity theory [11]; *iii)* devise a learning-aided distributed scheme to improve reliability in cooperative navigation; and *iv)* testing the developed algorithm/system on unmanned *Jackal* mobile robots at the University of Waterloo RoboHub.

Pre-requisites: Linear systems, constrained optimization, machine/deep learning, graph theory, and MATLAB/SIMULINK®
Desirable: System identification, observer design, distributed estimation

Learning Outcomes:

- Developing visual-inertial navigation solutions by data fusion and constrained optimization
- Understanding design for continuous-time and discrete-time dynamics
- Designing distributed observer to enhance navigation in a cooperative scheme through connectivity
- Implementing machine learning tools for system identification and withing the structure of distributed observers for shared perception
- Working with ROS and Vision/GPS/LiDar sensor on *Clearpath* mobile robotic platforms in real-time implementation

References

[1] Xiaojing Song, Lakmal D Seneviratne, and Kaspar Althoefer. A kalman filter-integrated optical flow method for velocity sensing of mobile robots. *IEEE/ASME Transactions on Mechatronics*, 16(3):551–563, 2011.

[2] Jiquan Ngiam, Aditya Khosla, Mingyu Kim, Juhan Nam, Honglak Lee, and Andrew Y Ng. Multimodal deep learning. In *ICML*, 2011.

[3] David Caruso, Alexandre Eudes, Martial Sanfourche, David Vissière, and Guy Le Besnerais. A robust indoor/outdoor navigation filter fusing data from vision and magneto-inertial measurement unit. *Sensors*, 17(12):2795, 2017.

[4] Jilin Mei, Biao Gao, Donghao Xu, Wen Yao, Xijun Zhao, and Huijing Zhao. Semantic segmentation of 3d lidar data in dynamic scene using semi-supervised learning. *IEEE Transactions on Intelligent Transportation Systems*, 21(6):2496–2509, 2019.

[5] Tong Qin, Peiliang Li, and Shaojie Shen. Vins-mono: A robust and versatile monocular visual-inertial state estimator. *IEEE Transactions on Robotics*, 34(4):1004–1020, 2018.

[6] Rong Kang, Lu Xiong, Mingyu Xu, Junqiao Zhao, and Peizhi Zhang. Vins-vehicle: A tightly-coupled vehicle dynamics extension to visual-inertial state estimator. In *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, pages 3593–3600. IEEE, 2019.

[7] Maryam Kamgarpour and Claire Tomlin. Convergence properties of a decentralized kalman filter. In *2008 47th IEEE Conference on Decision and Control*, pages 3205–3210. IEEE, 2008.

[8] Reza Olfati-Saber and Parisa Jalalkamali. Coupled distributed estimation and control for mobile sensor networks. *IEEE Transactions on Automatic Control*, 57(10):2609–2614, 2012.

[9] Fabio Pasqualetti, Antonio Bicchi, and Francesco Bullo. Consensus computation in unreliable networks: A system theoretic approach. *IEEE Transactions on Automatic Control*, 57(1):90–104, 2011.

[10] Yarin Gal and Zoubin Ghahramani. Dropout as a bayesian approximation: Representing model uncertainty in deep learning. In *international conference on machine learning*, pages 1050–1059, 2016.

[11] Anne Romer, Jan Maximilian Montenbruck, and Frank Allgöwer. Determining dissipation inequalities from input-output samples. *IFAC-PapersOnLine*, 50(1):7789–7794, 2017.

Project Proposals for Waterloo-KIT Collaborative Research

Ehsan Hashemi (University of Waterloo–MME) and Prof. Sören Hohman (KIT–IRS)
July 28, 2020

1. **Safe Merging for Automated-Natural Driving Systems**

   Overview of Project: Safe merging within the traffic flow in highways is an essential component for natural human drivers and advanced driver-assistance systems (ADAS). This problem is even more complex and crucial when the merging is happening between an autonomous vehicle (AV) and a natural human driver. Existing solutions in intelligent transportation system are generally focused on merging between two (or more) fully automated driving systems by using machine learning and leveraging advances in connectivity between the vehicle and infrastructure, or relying on accurate vehicle and tire models in AVs. However, such architectures for trajectory planning and guidance control between a human and a fully (or partially) automated driving systems in merging scenarios are prohibitively inefficient due to: *i)* not having access to the natural drivers' targets and more specifically cost functions; and *ii)* computational complexities and corner cases in data-driven methods for a control system having autonomous-human components. This project aims to develop a safe control strategy for automated driving systems, in highway merging scenarios, in presence of other vehicles with human drivers, by forming the problem in a game-theoretic representation and investigating how Machine Learning can contribute to adaptation of the controller.

   Project Specifics and Objectives: This research project aims to develop a safe non-cooperative (or cooperative) game-theoretic based control strategy and motion planning in highway merging for AVs while maintaining vehicle lateral stability by using available local sensory information (LiDar, radar, vision, IMU, steering, and wheel speed) and considering actuators' bandwidth and the combined-slip effect in the vehicle dynamics. The combined-slip tire forces is a contributor in such merging maneuvers due to quick acceleration/brake requests (by the motion planner) that result in considerable drop in lateral tire forces, thus affect vehicle stabilization and safety.

   You will first model the vehicle's combined longitudinal/lateral dynamics by considering the actuators' (i.e., active front steering and brakes) bandwidth and include the above mentioned available measurements that provide information on neighbour objects/vehicles position, ego vehicle localization, and vehicle states, such as sideslip and corner slip ratios. (see [1, 2, 3, 4, 5, 6]). Then, you will form a game-theoretic representation for two players (i.e., the ego autonomous vehicle and a regular vehicle with natural human driver) which do not have access to each others' cost functions and objectives for path tracking, stability, and handling criteria; you will also investigate how machine learning helps identification of major objective function components for each player, thus affect safety. Further challenges are:

   - Inter-vehicular distances and relative speeds are prone to error and disturbances based on GPS coverage/bandwidth as well as radar and vision system accuracy; you need to consider such disturbances and uncertainties in the model development and controller design

- Vehicle's corner/tire slip information, which affect lateral stability, is available only for the ego autonomous vehicle. Thus, based on consecutive observation of the regular vehicle with human driver, you need to investigate what states could be used in a non-cooperative game to quantify vehicle stabilization and tracking objectives in a game setting
- Varying road surface friction and robustness of a safe merging control strategy to major model parameters are challenges that needs to be studied and tackled.

More specifically, tasks to achieve main objectives include: *i)* develop a new merging model in a game setting by including tire slips, actuator dynamics/bandwidth, and longitudinal/lateral dynamics for the combined automated-natural driving systems, containing an ego AV and a regular vehicle; *ii)* characterize how robust is the control strategy due to uncertainties in the model (such as road friction), noises in the measurements (IMU, wheel speed, and steering), and errors in the localization and perception algorithms; *iii)* investigate how machine learning methods can contribute to identification of model parameters (by Recurrent Neural Networks, Locality-Sensitive Hashing, Long Short-Term Memory, etc.) and adaptation of the control law (by Reinforcement Learning); and *iv)* investigate a possible mitigation plan for measurement loss (such as GPS perception) through V2X connectivity.

Pre-requisites: Linear systems theory, game theory, machine learning, and MATLAB/SIMULINK®
Desirable: System identification and robust control theory

Learning Outcomes:

- Modeling vehicle longitudinal/lateral dynamics by considering the combined-slip effect and actuators' bandwidth
- Designing game-theoretic based controllers for highway merging between two vehicles/players that do not have access to the other player's cost function and objectives
- Understanding design for continuous-time and discrete-time dynamics
- Investigating robustness of such non-cooperative merging game to model uncertainties
- Applying machine learning methods (discussed above) for local model identification and game control law adaptation

References

[1] Ehsan Hashemi, Milad Jalali, Amir Khajepour, Alireza Kasaiezadeh, and Shih-Ken Chen. Vehicle stability control: Model predictive approach and combined-slip effect. *IEEE/ASME Transactions on Mechatronics*, 2020.

[2] Junqing Wei, John M Dolan, and Bakhtiar Litkouhi. Autonomous vehicle social behavior for highway entrance ramp management. In *2013 IEEE Intelligent Vehicles Symposium (IV)*, pages 201–207. IEEE, 2013.

[3] Yangliu Dou, Fengjun Yan, and Daiwei Feng. Lane changing prediction at highway lane drops using support vector machine and artificial neural network classifiers. In *2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, pages 901–906. IEEE, 2016.

[4] Niclas Evestedt, Erik Ward, John Folkesson, and Daniel Axehill. Interaction aware trajectory planning for merge scenarios in congested traffic situations. In *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, pages 465–472. IEEE, 2016.

[5] Jackeline Rios-Torres and Andreas A Malikopoulos. A survey on the coordination of connected and automated vehicles at intersections and merging at highway on-ramps. *IEEE Transactions on Intelligent Transportation Systems*, 18(5):1066–1077, 2017.

[6] Roman Schmied and Patrizio Colaneri. Mixed $h_2 - h_\infty$ control for automated highway driving. *Mechatronics*, 57:63–72, 2019.