AMR 2023/2024: Final Projects

A final project consists of (1) studying papers, notes or documentation on a specific subject (2) performing simulations on a software platform (3) writing a report and giving a presentation (with slides).

Each project must be carried out by a group of **3 students**. To apply, send me an e-mail message with the composition of your group (one message per group, all members in cc:) and a list of **3** projects (identified by their number) in order of preference. Projects will be assigned on a FIFO basis. 1 or 2-student groups can also apply, but I will merge them into groups of 3. The deadline for applying is **November 29**.

Once your group has been assigned a project, you will meet with your supervisor(s) to discuss the work in detail. When your project is completed, you must send me an e-mail with the report and then I will set up a presentation date. All projects must be completed by **June 30, 2024**.

This is the list of the available projects, with the name of the supervisor(s) in parentheses, followed by a short synopsis (including bibliography) of each project.

FP1. WMR control with UKF-based wheel slippage estimation (F. D'Orazio)
FP2. Grasping on-the-move using a mobile manipulator (F. D'Orazio)
FP3. Obstacle avoidance: Control Barrier Functions vs Artificial Potential Fields (T. Belvedere)
FP4. Safe robot navigation in crowds using Nonlinear MPC (T. Belvedere, M. Cipriano, F. D'Orazio)
FP5. Vision-based human tracking and avoidance with TIAGo (T. Belvedere, M. Cipriano)
FP6. Quadruped motion generation in a world of stairs (M. Cipriano)
FP7. Kinodynamic motion planning for steerable WMRs (M. Cipriano)
FP8. Vehicle control via MPC with cascaded models (N. Scianca)
FP9. Vehicle control via Learning MPC with error dynamics regression (N. Scianca)

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1. WMR control with UKF-based wheel slippage estimation

The model of a wheeled mobile robot encodes the nonholonomic constraint which results from assuming no slip between the ground and the wheels. However, in some applications slip cannot be neglected and controllers that are based on a no-slip model may not work properly. The aim of this project is to robustify the control performance by compensating the wheel slippage as estimated through an Unscented Kalman Filter applied on the TIAGo mobile manipulator. To validate the implementation, simulations must be performed in Python or C++ (using Gazebo + ROS), or in Matlab.

- Iossaqui et al, "Slip estimation using the unscented Kalman Filter for the tracking control of mobile robots", COBEM 2011

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2. Grasping on-the-move using a mobile manipulator

When executing a multi-step task, most architectures for controlling a mobile manipulator will only consider only the immediate subgoal. However, it has been shown that considering the next objective (e.g. grasping while moving in a pick and place operation) allows to improve the performance of the robot (Burgess-Limerick et. al 2023). The aim of the project is to implement the architecture proposed in that work on the TIAGo mobile manipulator. To validate the implementation, simulations must be performed in Python or C++ (using Gazebo + ROS), or in Matlab.

- Burgess-Limerick et al, "An architecture for reactive mobile manipulation on-the-move", ICRA 2023

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3. Obstacle avoidance: Control Barrier Functions vs Artificial Potential Fields

One of the most fundamental functionalities of mobile robot control is obstacle avoidance, which allows robots to navigate in environments where unforeseen obstacles might be present. Historically, Artificial Potential Fields have been used as a simple and effective way to steer robots away from obstacles. More recently, Control Barrier Functions have emerged as a way to impose safety constraints on nonlinear systems and have been extensively used for obstacle avoidance. The two methods share some conceptual similarities, however they can provide somewhat different results making one more suitable than the other (Singletary et al 2021). The goal of the project is to perform a comparison between these two methods highlighting similarities and differences. This project must be implemented in Python/C++ using ROS. Simulations must be performed in Gazebo to validate the implementation.

- Singletary et al, "Comparative Analysis of Control Barrier Functions and Artificial Potential Fields for Obstacle Avoidance", IROS 2021

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4. Safe robot navigation in crowds using Nonlinear MPC

Mobile robots are increasingly used in service applications (e.g. food delivery, cleaning, patrolling), where they have to navigate alongside humans. In such situations, the robot should guarantee not only its own safety, but also the safety of the humans, which is of utmost importance. The aim of this project is to implement a Nonlinear MPC controller for the TIAGo mobile manipulator moving in a human crowd. The NMPC controller must generate a safe motion to reach a target position while avoiding collisions with humans trough obstacle avoidance constraints (Vulcano et al 2022). This project must be implemented in Python/C++ using ROS. Simulations must be performed in Gazebo to validate the implementation.

- Vulcano et al, "Safe Robot Navigation in a Crowd Combining NMPC and Control Barrier Functions", CDC 2022

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5. Vision-based human tracking and avoidance with TIAGo

Mobile robots are increasingly used in service applications (e.g. food delivery, cleaning, patrolling), where they have to navigate alongside humans. In recent work (Vulcano et al 2022) a framework to navigate among humans using a laser rangefinder has been developed. However, using only this sensor, it is not possible to differentiate between humans and other obstacle types, so that the current implementation is limited to environments where only humans are present. The goal of the project is to extend this work by implementing a vision-based human detection and tracking module to estimate their current position and velocity, while controlling the pan and tilt angles of the camera mounted on the robot to keep the humans in the field of view. This project must be implemented in Python/C++ using ROS. Simulations must be performed in Gazebo to validate the implementation.

- Vulcano et al, "Safe Robot Navigation in a Crowd Combining NMPC and Control Barrier Functions", CDC 2022

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6. Quadruped motion generation in a world of stairs

Legged robots have the potential to navigate complex and uneven terrains, using a combination of footstep planning and Model Predictive Control for gait generation (Cipriano et al 2023). The aim of this project is to develop a navigation stack for a quadruped robot, similar to the one presented for a humanoid in a recent work (Cipriano et al 2023). The framework will be composed of an offline footstep planner based on randomized algorithms and an MPC for walking gait generation. Simulations in Python must be performed to validate the implementation.

- Cipriano et al, "Humanoid motion generation in a world of stairs", RAS 2023

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7. Kinodynamic motion planning for steerable WMRs

Mobile robots equipped with multiple steerable wheels are known to have greater maneuverability with respect to other wheeled mobile robots due to their omnidirectionality (Robuffo Giordano et al 2009); oreover, they are able to manipulate larger payloads with respect to omnidirectional robots equipped with mecanum wheels or omni wheels. The aim of this project is to develop a kinodynamic RRT* motion planning algorithm for steerable WMRs based on a recent work (Webb et al 2013). Simulations in Python must be performed to validate the implementation.

- Robuffo Giordano et al, "On the Kinematic Modeling and Control of a Mobile Platform Equipped with Steering Wheels and Movable Legs", ICRA 2009
- Webb et al, "Kinodynamic RRT*: Asymptotically Optimal Motion Planning for Robots with Linear Dynamics", ICRA 2013

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8. Vehicle control via MPC with cascaded models

In order to accurately represent their dynamics, vehicle models can get rather complex. Using Model Predictive Control (MPC) on such complex models can be prohibitive due to the difficulty of solving the optimization problem in real time. This can be alleviated by using models of different complexity across the prediction horizon of the MPC. In particular, one should use a very accurate model for the first part of the horizon, where dynamics are critical for stability, and a simplified model for the later part. The goal of this project is to replicate the results of a recent work (Laurense and Gerdes 2021), in which such an algorithm is proposed in the context of vehicle control. Students are free to choose the implementation platform, but it is suggested to use the casADi interface for optimization, either in Python or MATLAB.

- Laurense and Gerdes, "Long-Horizon Vehicle Motion Planning and Control Through Serially Cascaded Model Complexity", IEEE Trans on Control Systems Technology, 2021

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9. Vehicle control via Learning MPC with error dynamics regression

Learning Model Predictive Control (LMPC) is a powerful technique (Rosolia and Borrelli 2017) which uses a data-driven approach to improve the performance of Model Predictive Control in iterative tasks. As more iterations of the tasks are performed, safe states are added to a safe set, which is later used to construct terminal constraints and terminal costs. A recent work (Xue et al, 2023) proposes an extension of LMPC which also includes error dynamics regression for improving predictive accuracy. The goal of this project is to implement such a scheme in a vehicle control context. Students are free to choose the implementation platform, but it is suggested to use the casADi interface for optimization, either in Python or MATLAB.

- Rosolia and Borrelli, "Learning Model Predictive Control for Iterative Tasks: A Data-Driven Control Framework", IEEE Trans on Automatic Control, 2017
- Xue et al, "Learning Model Predictive Control with Error Dynamics Regression for Autonomous Racing", ICRA 2024 (arXiv preprint), 2023