AMR 2024/2025: 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 (hence, the sooner you apply, the more likely you are to get one of your preferred projects). 1- or 2-student groups can also apply, but I will merge them into groups of 3. The deadline for applying is **November 28**.

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, 2025**.

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. Trajectory optimization for humanoids via centroidal dynamics (Scianca)
FP2. Task-priority control for mobile manipulators (D'Orazio)
FP3. Practically safe controllers for mobile robots (D'Orazio)
FP4. Humanoid MPC based on centroidal dynamics (Scianca)
FP5. Multi-room navigation for TIAGo using RRT* (Cipriano, D'Orazio)
FP6. Differentiable collision detection for autonomous driving (Cipriano)
FP7. Humanoid navigation using control barrier functions (Cipriano)
FP8. Autonomous vehicle drifting using nonlinear MPC (Cipriano)
FP9. MOD-RRT* for real-time planning in dynamic environments (Habib)

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1. Trajectory optimization for humanoids via centroidal dynamics (Scianca)

The Centroidal Dynamics is a reduced representation of a floating-base robot that includes linear and angular momentum. Compared to other simplified descriptions, it does not neglect the angular momentum, and thus allows to perform more dynamic motions. Tazaki [1] proposes to approximate the solution in order to have closed form expressions, leading to very efficient trajectory optimization. The goal of this project is to reproduce some of the results in the paper, visualize the solution of the optimization and track them on a simulated humanoid robot. A working implementation of humanoid robot locomotion with a different technique will be provided, depending on the choice of the students, in Python or C++.

- Tazaki, "Trajectory Generation for Legged Robots Based on a Closed-Form Solution of Centroidal Dynamics", Robotics and Automation Letters, 2024

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2. Task-priority control for mobile manipulators (D'Orazio)

The redundancy of mobile manipulators allows them to perform multiple tasks simultaneously, such as avoiding obstacles with the base while tracking a task-space trajectory with the end-effector. In the referenced article, a differential task-priority inverse kinematic controller was proposed to allow an omnidirectional mobile manipulator to perform a primary task while avoiding obstacles, along with a secondary task focused on maximizing manipulability, by solving a cascade of two Quadratic Programs. The goal of this project is to implement the same controller on the TIAGo robot, which has a nonholonomic mobile base, and to avoid obstacles using the Control Barrier Function framework. To validate the implementation, simulations must be performed in Python or MATLAB.

- Schoellig et al, "Mobile manipulation in unknown environments with differential inverse kinematics control", CRV 2021

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3. Practically safe controllers for mobile robots (D’Orazio)

Robot control often involves enforcing safety constraints, either as a primary objective or a secondary aspect of the control strategy. Control Barrier Functions offer a mechanism to encode these constraints, ensuring that system inputs prevent the system from leaving the safe set. However, commanding safety-critical systems with digital controllers introduces potential safety violations due to sampling effects. This challenge can be addressed by formalizing the concept of practical safety, namely ensuring sufficiently high sampling frequencies, with the Input-to-State Safety framework. The goal of this project is to implement the method described in the referenced article under various scenarios.

- Ames et al, Sample-and-Hold Safety with Control Barrier Functions, ACC 2024

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4. Humanoid MPC based on centroidal dynamics (Scianca)

The Centroidal Dynamics is a reduced representation of a floating-base robot that includes linear and angular momentum. Compared to other simplified descriptions, it does not neglect the angular momentum, and thus allows to perform more dynamic motions. However, it introduces nonlinearities in the model, and therefore controllers that use it cannot usually guarantee feasibility and stability. The referenced paper proposes a technique to achieve such guarantees without introducing additional constraints. The goal of this project is to reproduce some of the results in the paper, and present them along with an explanation of the theoretical properties of the scheme. A working implementation of humanoid robot locomotion with a different technique will be provided, depending on the choice of the students, in Python or C++.

- Elobaid et al., “Online Nonlinear Centroidal MPC with Stability Guarantees for Robust Locomotion of Legged Robots”, arXiv, 2024

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5. Multi-room navigation for TIAGo using RRT* (Cipriano, D’Orazio)

Mobile robots are increasingly being utilized in service applications, requiring them to navigate in human-like environments. In many cases, these robots must move between rooms, such as for tasks like food delivery or fetching items in an office setting. Multi-room navigation necessitates a motion planner and a motion generation module implemented as a nonlinear Model Predicting Control, in order to compute feasible commands and impose constraints. The goal of this project is to implement the RRT* algorithm on the TIAGo robot, allowing it to navigate through rooms. To validate the implementation, simulations must be performed in Python or C++.

- Karaman and Frazzoli, “Optimal Kinodynamic Motion Planning using Incremental Sampling-based Methods”, CDC 2010

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6. Differentiable collision detection for autonomous driving (Cipriano)

Collision detection is essential in motion planning and control techniques for robotic systems. There exists a vast number of approaches in literature, most of them are non-differentiable, and cannot be used directly in gradient-based optimization tools. The aim of this project is to implement DCOL, a differentiable collision-detection framework for a set of convex primitives, and use it within a trajectory optimization problem to compute a motion plan for an autonomous vehicle in a cluttered environment. Simulations in Python must be performed to validate the implementation.

- Tracy et al, “Differentiable Collision Detection for a Set of Convex Primitives”, ICRA 2023

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7. Humanoid navigation using control barrier functions (Cipriano)

Bipedal robot navigation in cluttered environments is a challenging task that must be addressed and solved in real time to allow humanoids to be deployed in the real world. Existing approaches often decouple path planning from gait generation, due to high computational requirements caused by the underlying dynamics of the robot. The aim of this project is to develop a unified path and gait planning framework which allows a humanoid robot to navigate an environment full of obstacles. The approach will use the LIP as a template model for walking, together with discrete control barrier functions for obstacle avoidance. Simulations in Python must be performed to validate the implementation.

- Peng et al, “Real-Time Safe Bipedal Robot Navigation using Linear Discrete Control Barrier Functions”, ArXiV, 2024

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8. Autonomous vehicle drifting using nonlinear MPC (Cipriano)

Controlling a vehicle at their performance limits is a challenging problem of significant importance, not only for autonomous racing, but also for the safety of autonomous driving. For example, skidding may occur in presence of ice, and it is desirable to control the vehicle back to its nominal working conditions. The aim of this project is to develop a framework based on nonlinear MPC to generate and track dynamic drifting maneuvers for a car, using a kinodynamic bicycle model. Simulations in Python must be performed to validate the implementation.

- Bellegarda et al, “Dynamic Vehicle Drifting With Nonlinear MPC and a Fused Kinematic-Dynamic Bicycle Model”, L-CSS 2021

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9. MOD-RRT* for real-time planning in dynamic environments (Habib)

Mobile robots are increasingly deployed in dynamic environments, where they must efficiently navigate while avoiding unforeseen obstacles. MOD-RRT* is a sampling-based algorithm that generates and replans paths optimized for length and smoothness, outperforming traditional static planning methods. However, it does not account for the robot dynamics, which can result in paths that are infeasible for the robot to follow in real-world scenarios. The objective of this project is to implement and extend the MOD-RRT* algorithm by incorporating the robot dynamics. To generate dynamically feasible paths and perform real-time replanning in dynamic environments. The project must be implemented in Python/C++ using ROS, and simulations must be conducted in Gazebo to validate the approach.

- J. Qi, H. Yang and H. Sun, ”MOD-RRT*: A Sampling-Based Algorithm for Robot Path Planning in Dynamic Environment,” IEEE Transactions on Industrial Electronics, 2021