AMR 2022/2023: 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 numbers) 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 **December 3**.

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 **April 30, 2023**.

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. Autonomous humanoid navigation in multi-floor environments (M. Cipriano)
FP2. A navigation stack for a skid-steering mobile robot (M. Cipriano)
FP3. Safe robot navigation in crowds with TIAGo (M. Cipriano, T. Belvedere and S. Tarantos)
FP4. Optimal kinodynamic planning for nonlinear hybrid systems (M. Cipriano and N. Scianca)
FP5. Planning throwing motions for mobile manipulators (S. Tarantos)
FP6. Real-time generation of collision-free motions for mobile manipulators (S. Tarantos)
FP7. Generation of minimum-sensitivity trajectories for differential-drive robots (T. Belvedere)
FP8. Model-free control barrier functions for obstacle avoidance (T. Belvedere)
FP9. Improving the performance of RRT planners using informed sampling (N. Scianca)
FP10. Planning humanoid motion on uneven ground using the gravito-inertial wrench cone (N. Scianca)

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1. Autonomous humanoid navigation in multi-floor environments

Recent advances in planning and control techniques for humanoid robots, such as that presented in (Ferrari et al 2019), have demonstrated the possibility to make them navigate in complex uneven terrains. However, to keep the representation of the environment efficient, an elevation map is typically used, losing the possibility to represent structures composed of multiple levels. The aim of this project is to extend this humanoid navigation framework by implementing a footstep planner based on multi-level surface maps (Triebel et al 2006), hence allowing navigation in environments composed of multiple floors. Simulations must be performed to validate the implementation in C++ or Python.

- Ferrari et al, “An Integrated Motion Planning/Controller for Humanoid Robots on Uneven Ground”, ECC 2019
- Triebel et al, “Multi-Level Surface Maps for Outdoor Terrain Mapping and Loop Closing”, IROS 2006

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2. A navigation stack for a skid-steering mobile robot

In the past few years, wheeled mobile robots have become capable of navigating in challenging environments thanks to major advances in perception, planning and control. Nevertheless, only recently the ability of autonomous navigation has been achieved in rough and unknown environments such as those of DARPA SubT Challenge. The aim of this project is to develop a navigation stack for a skid-steering mobile robot based on (Caracciolo et al 1999) that allows it to navigate rough environments. The framework will be composed of an anytime planner (Karaman et al 2011) that will continuously generate trajectories based on an estimated traversability of the terrain (Wermelinger et al 2016). This project must be implemented in C++ or Python. Simulations must be performed to validate the implementation (Clearpath Robotics Husky with Gazebo).

- Caracciolo et al, “Trajectory Tracking Control of a Four-Wheel Differentially Driven Mobile Robot”, ICRA 1999
- Karaman et al, “Anytime Motion Planning using the RRT*”, ICRA 2011
- Wermelinger et al, “Navigation Planning for Legged Robots in Challenging Terrain”, IROS 2016

3. Safe robot navigation in crowds with TIAGo

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 develop a safe navigation framework for the TIAGo mobile manipulator moving in a human crowd. The framework will be composed of a crowd prediction module (Vulcano et al 2022) and a simple motion generation module based on a quadratic program that considers collision avoidance constraints built upon control barrier functions (Ames et al 2019). This project must be implemented in C++ or Python 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
- Ames et al, “Control Barrier Functions: Theory and Applications”, ECC 2019

4. Optimal kinodynamic planning for nonlinear hybrid systems

Sampling-based motion planning algorithms such as PRM and RRT are commonly used to solve planning problems due to their ability to efficiently find solutions. Nevertheless, when applied to kinodynamic and hybrid systems, they typically perform poorly and they do not guarantee probabilistic completeness. The aim of this project is to implement R3T (Wu et al 2020), a probabilistic complete and asymptotically optimal variant of RRT for kinodynamic planning of nonlinear hybrid systems, and compare it with RG-RRT (Shkolnik et al 2009) and RRT (LaValle et al 2001). Simulations must be performed to validate the implementation.

- Wu et al, “R3T: Rapidly-exploring Random Reachable Set Tree for Optimal Kinodynamic Planning of Nonlinear Hybrid Systems”, ICRA 2020
- Shkolnik, “Reachability-guided sampling for planning under differential constraints”, ICRA 2009
- LaValle and Kuffner, “Randomized Kinodynamic Planning”, IJRR 2001

5. Planning throwing motions for mobile manipulators

Consider a mobile manipulator that must carry an object from an initial location to a final one. In certain cases, incorporating a throwing action can increase the robot workspace and reduce the task duration. The objective of this project is to plan a fast throwing motion for a planar mobile manipulator. The motion planning problem will be formulated as an Optimal Control Problem (OCP) that will be solved using numerical optimization. For this purpose, the Optimization Toolbox of MATLAB will be used. The resulting motion will be checked for its safety in terms of balance loss.

- Lombai and Szederkenyi, “Throwing motion generation using nonlinear optimization on a 6-degree-of-freedom robot manipulator”, 2009 IEEE Int Conf on Mechatronics
- Kolyubin and Shiriaev, “Planning Longest Pitch Trajectories for Compliant Serial Manipulators”, IROS 2016
- Tarantos and Oriolo, "Real-time motion generation for mobile manipulators via NMPC with balance constraints", MED 2022

6. Real-time generation of collision-free motions for mobile manipulators

Consider a mobile manipulator that must execute a task requiring aggressive motions. To enforce kinodynamic feasibility, the robot dynamic model is used as a prediction model, while the robot safety in terms of balance and collision avoidance is enforced via appropriate constraints. This project focuses on the collision avoidance constraints and the way in which their effectiveness is affected by the size of the prediction horizon. In particular, a Nonlinear Model Predictive Control (NMPC) scheme should be designed comparing different collision avoidance constraints: (1) a purely distance-based constraint (2) a constraint built via Control Barrier Functions (3) a constraint based on the Velocity Damper approach. Implementation of the NMPC will be based on the MATLAB interface of ACADO Toolkit.

- Tarantos and Oriolo, "Real-time motion generation for mobile manipulators via NMPC with balance constraints", MED 2022
- Faverjon and Tournassoud, “A local based approach for path planning of manipulators with a high number of degrees of freedom”, ICRA 1987

7. Generation of minimum-sensitivity trajectories for differential-drive robots

Robotic control systems need to operate in the real world, thus in uncertain conditions. For example, the parameters of the model may be uncertain, leading to a loss of performance of the controller during the actual deployment. A possible way to tackle this problem and achieve better performance is to design motions that are less susceptible to such uncertainties. Following this approach, (Robuffo Giordano et al 2018) proposed a method to generate trajectories that minimize the sensitivity of the closed-loop system (including the controller) to parametric uncertainties. The objective of the project is to showcase this method applying it to the trajectory generation of a differential-drive robot. The simulations can be performed in either Python or MATLAB.

- Robuffo Giordano et al, Trajectory generation for minimum closed-loop state sensitivity, ICRA 2018

8. Model-free control barrier functions for obstacle avoidance

Mobile robots are often assigned safety objectives that can be formulated as the requirement to keep the robot in a safe set (i.e., set invariance). A common example is obstacle avoidance, where the robot must remain in the free configuration space in order to avoid collision with obstacles. To this aim, Control Barrier Functions (CBFs) (Ames et al., 2019) have been proposed as a rather general way to synthesize controllers that directly enforce the invariance of the safe set. This technique however requires a sufficiently accurate model of the robot to prove safety. More recently, (Molnar et al., 2021) proposed a method to provide such safety guarantees in a (more desirable) model-free fashion. The objective of the project is to analyze this method in an obstacle avoidance scenario, comparing it with standard CBFs and highlighting its advantages and/or limitations. The comparison should be carried out implementing the methods in MATLAB simulations.

- Ames et al, “Control Barrier Functions: Theory and Applications”, ECC 2019
- Molnar et al, “Model-free safety-critical control for robotic systems”, RA-L 2021

9. Improving the performance of RRT planners using informed sampling

RRT* is a variant of RRT that produces optimal trajectories according to a chosen criterion. RRT* is asymptotically optimal, meaning that it converges to the optimal solution, but this convergence can be quite slow. (Gammel et al, 2014) propose a way to improve this convergence by using the currently available solution in order to inform sampling of subsequent expansion attempts. The objective of the project is to replicate the results of that paper and compare them to classic RRT*. A similar algorithm which uses Monte Carlo Markov Chain sampling can also be explored for comparison. Simulations can be carried out using MATLAB.

- Gammel et al, “Informed RRT: Optimal Sampling-Based Path Planning Focused via Direct Sampling of an Admissible Ellipsoidal Heuristic”, IROS 2014
- Yi et al, “Generalizing Informed Sampling for Asymptotically-Optimal Sampling-Based Kinodynamic Planning via Markov Chain Monte Carlo”, ICRA 2018

10. Planning humanoid motions on uneven ground using the gravito-inertial wrench cone

The Zero Moment Point (ZMP) is a convenient tool to characterize bipedal balance on flat ground, because it encodes requirements on the contact forces as a simple geometric constraint (i.e., the ZMP itself must be contained within the support polygon of the robot). For more complex contact configurations, the ZMP can be easily extended but the equivalent of the support polygon is difficult to define. (Caron et al. 2015) proposed a procedure to encode a set of constraints on contact forces as an equivalent constraint on the gravito-inertial wrench, which in practice constrains the allowed accelerations at the CoM, and is equivalent to using an extended ZMP formulation. The objective of the project is to reconstruct the gravito-inertial wrench cones for a given sequence of contact configurations, and use them to plan a COM trajectory for the humanoid. Simulations should be carried out MATLAB.

- Caron et al, “Leveraging Cone Double Description for Multi-contact Stability of Humanoids with Applications to Statics and Dynamics”, RSS 2015