AMR 2021/2022: 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 6**.

Once your group has been assigned a project, you will meet with your supervisor 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 **July 31, 2022**.

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

FP1. Stochastic MPC for humanoid gait generation (F. Smaldone)
FP2. Comparison between whole-body MPC and hierarchical architectures for running (F. Smaldone)
FP3. Optimal sampling-based footstep planning using Informed RRT* (M. Cipriano)
FP4. Autonomous humanoid navigation in large-scale environments (M. Cipriano)
FP5. Planning parking maneuvers for a car-trailer vehicle (T. Belvedere)
FP6. Enforcing mobile robot safety under input constraints (T. Belvedere)
FP7. Multi-contact IK-CS solver for humanoid robots (P. Ferrari)
FP8. Comparing classic and primitive-based versions of kinodynamic RRT* (P. Ferrari)
FP9. Grid-based path planning for a differential drive robot (G. Turrisi)
FP10. Improving performance in humanoid walking using iterative learning (N. Scianca)
FP11. Safe navigation through Hamilton-Jacobi reachability analysis (V. Modugno)

---

1. Stochastic MPC for humanoid gait generation

In the presence of disturbances or measurement/process noise, the performance of MPC-based controllers typically deteriorates, possibly leading to constraint violation. In the case of humanoid gait generation, this can cause the loss of dynamic balance and internal instability with the subsequent fall of the robot. The objective of this project is to implement a Stochastic-MPC-based gait generation algorithm for humanoids which is able to guarantee robustness in the presence of noise and/or disturbances, based on the two papers given as references. The designed algorithm will have to be validated through dynamic simulations on an OP-3 humanoid.

- Gazar et al, "Stochastic and Robust MPC for Bipedal Locomotion: A Comparative Study on Robustness and Performance", Humanoids 2021
- Smaldone et al, "ZMP Constraint Restriction for Robust Gait Generation in Humanoids", ICRA 2020

---

2. Comparison between whole-body MPC and hierarchical architectures for running

Differential Dynamic Programming (DDP) is a promising framework for optimal control applied to legged locomotion, allowing to generate complex whole-body motions in almost real time. On the other hand, the classical approaches for gait generation typically rely on hierarchical architectures where trajectories are first generated using simplified models and then tracked via kinematic control. The objectives of the project are (1) to use the Crocoddyl library to implement a whole-body DDP-based algorithm for generation of running gaits on a simulated HRP-4 robot and (2) to compare its performance to that of a hierarchical architecture which will be provided to the students.

- Mastalli et al, "Crocoddyl: An Efficient and Versatile Framework for Multi-Contact Optimal Control", ICRA 2020
- Smaldone et al, "MPC-Based Gait Generation for Humanoids: from Walking to Running", I-RIM 2021

3. Optimal sampling-based footstep planning using Informed RRT*

Rapidly-exploring random trees (RRTs) are popular in motion planning because they find solutions efficiently to single-query problems. Optimal RRTs extend them to the problem of finding the optimal solution, but in doing so asymptotically find the optimal path from the initial state to every state in the planning domain, which is not only inefficient but also inconsistent with their single-query nature. For problems seeking to minimize path length, the subset of states that can improve a solution can be described by a prolate hyperspheroid. The aim of this project is to implement Informed RRT* (Gammell et al.), an extension of RRT* which directly samples states from the abovementioned hyperspheroid, and to test it within our humanoid navigation framework (Ferrari et al.). Simulations must be performed to validate the implementation. This project must be implemented in C++.

- Gammell et al., “Informed RRT*: Optimal Sampling-based Path Planning Focused via Direct Sampling of an Admissible Ellipsoidal Heuristic”, IROS 2014
- Ferrari et al., “An Integrated Motion Planning/Controller for Humanoid Robots on Uneven Ground”, ECC 2019

4. Autonomous humanoid navigation in large-scale environments

Autonomous navigation in large-scale environments remains a major challenge in robotic systems. Recent research ideas presented during the DARPA SubT Challenge showed that it is possible to explore and navigate complex unknown environments using both ground and aerial vehicles. The aim of this project is to extend our humanoid navigation framework (Ferrari et al.) by implementing a global-planner (Dang et al.) and by integrating it with our RRT*-based footstep planner, which will act as a local planner. Simulations must be performed to validate the implementation. This project must be implemented in C++.

- Dang et al., “Graph-based Subterranean Exploration Path Planning using Aerial and Legged Robots”, Journal of Field Robotics 2020
- Ferrari et al., “An Integrated Motion Planning/Controller for Humanoid Robots on Uneven Ground”, ECC 2019

5. Planning parking maneuvers for a car-trailer vehicle

Being a nonholonomic vehicle, planning parking maneuvers for a car-trailer vehicle requires accounting for the kinematic constraints on the system. In sampling-based planners like RRT, this can be done by sampling the input space and forward integrating the system generating dynamically feasible motion primitives. The car-trailer system is however unstable in backward motion, exhibiting the so-called "jackknifing" phenomenon, in which the hitch angle between the car and the trailer heading angles diverges, leading to a loss of maneuverability and ultimately to self collision. For this reason, planning backward trajectories requires special care. The project consists in the implementation of an RRT-based planner for the car-trailer vehicle using the Open Motion Planning Library (OMPL), possibly implementing the technique presented in the accompanying paper to stabilize backward motion primitives. The project must be implemented in C++.

- Evestedt et al, "Motion planning for a reversing general 2-trailer configuration using Closed-Loop RRT", IROS 2016
- https://ompl.kavrakilab.org/

6. Enforcing mobile robot safety under input constraints

Robot control typically requires the enforcement of some safety constraint, either as a primary or secondary goal of the control scheme. In this context, Control Barrier Functions provide a way to encode such constraints by ensuring that the inputs will not make the system leave the safe set. If there are no actuation limits, finding a valid CBF for many tasks is relatively straightforward. However, to provide true safety guarantees, the CBFs must be designed to account for input constraints when present, which is in general a difficult task. The goal of the project is to implement a method, presented in the papers below, to generate Input Constrained Control Barrier Functions for the control of a unicycle robot and simulate different scenarios.

- Agrawal et al, "Safe Control Synthesis via Input Constrained Control Barrier Functions", CDC 2021
- Ames et al, "Control barrier functions: Theory and applications." ECC 2019

7. Multi-contact IK-CS solver for humanoid robots

The aim of this project is to implement an inverse kinematics (IK) and centroidal statics (CS) solver for the HRP4 humanoid in multi-contact situations, i.e., when the robot establishes non-coplanar surface contacts with the environment using feet, hands and possibly other links. In particular, given a stance (i.e., a contact combination), the solver must generate a feasible humanoid configuration that satisfies the kinematic constraints yielded by the stance and guarantees static balance. The second objective requires the satisfaction of particular contact-stability conditions on each surface contact, which are commonly written in terms of (i) the contact forces at the surface vertices or (ii) the resulting contact wrench on the surface itself. The IK-CS solver must be implemented in C++, with both (i-ii) contact-stability criteria, and comparative simulations must be performed using CoppeliaSim.

- Bouyarmane et al, “Multi-contact motion planning and control,” Humanoid Robotics: A Reference 2018
- Caron et al, “Stability of surface contacts for humanoid robots: Closed-form formulae of the contact wrench cone for rectangular support areas,” ICRA 2015

8. Comparing classic and primitive-based versions of kinodynamic RRT*

Kinodynamic motion planning combines the search for a collision-free path with the underlying dynamics of the considered system. RRT* is recognized as one of the best techniques for motion planning thanks to its probabilistic completeness and asymptotic optimality properties. However, in its kinodynamic form, RRT* potentially needs multiple resolutions of two points boundary value problems (TPBVPs) at each iteration, which inevitably increases its computational cost. A recently introduced version of RRT* tries to overcome such computational challenge by involving a primitive-based approach: a catalogue of motion primitives is precomputed, solving TPBVPs before constructing the tree, and thus reducing the search at finding an appropriate concatenation of such primitives. The aim of this project is to implement the kinodynamic RRT* planner (in C++/CoppeliaSim or Matlab) in both the mentioned versions and to produce comparative simulations using a unicycle.

- Sakcak at al, “Sampling-based optimal kinodynamic planning with motion primitives,” Autonomous Robots 2019

9. Grid-based path planning for a differential drive robot

In the literature, different approaches exist for computing a path between two points in a known map, such as via sampling, nonlinear optimization, grid-based search etc. The latter is generally considered to be a viable solution when the dynamic constraint is not crucial for the obtained path, as in the case of a differential drive robot, and exhibits completeness, fast convergence and good replanning capability in the case of non-static environments. The aim of this project is to test and compare two different grid-based methods, namely D* (Stentz, 1994) and D* Lite (Koenig et al., 2005), implementing all the simulations in Matlab and CoppeliaSim.

- A. Stentz, "Optimal and efficient path planning for partially-known environments," ICRA 1994
- S. Koenig and M. Likhachev, "Fast replanning for navigation in unknown terrain," IEEE Transactions on Robotics 2005

10. Improving performance in humanoid walking using Iterative Learning

Walking can, to a certain extent, be considered a repetitive motion. Iterative Learning Control (ILC) consists of a wide class of approaches where a controller is designed in such a way to use data collected at previous iteration in order to improve its performance. In 2020, Wang et al proposed a technique to collect error measurements at previous steps on a walking humanoid, and employ them to correct the references for subsequent steps, with the objective of increasing performance. The goal of this project is to replicate the main ideas in this work, and analyze them in such a way to emphasize the benefits and drawbacks. Simulations should be produced initially in MATLAB, and possibly in the dynamic simulator DART.

- Wang et al. "Online Virtual Repellent Point Adaptation for Biped Walking using Iterative Learning Control", Humanoids 2020
- Englsberger et al. "Three-Dimensional Bipedal Walking Control Based on Divergent Component of Motion", T-RO 2015

11. Safe navigation through Hamilton-Jacobi reachability analysis

Guaranteeing performance and avoiding crashes in dynamic systems is of capital importance for safety-critical applications. In this context, a powerful tool for verification and validation of safety for controlled systems is represented by the Hamilton-Jacobi (HJ) reachability analysis. Briefly, with HB reachability analysis it is possible to compute the reach-avoid set, defined as the set of states from which the system can be driven to a target set while satisfying time-varying state constraints at all times. The objective of this project is to apply HB reachability to the problem of safely guiding a wheeled mobile robot in a dynamic environment in order to safely reach the desired destination. The project will be developed in MATLAB.

- Bansal et al, Hamilton-Jacobi Reachability: A Brief Overview and Recent Advances, CDC 2017