AMR 2019/2020: 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 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 larger groups. The deadline for applying is **December 15**.

Once your group has been assigned a project, we will set up a meeting to discuss the project in detail. You will be assigned a supervisor. When your project is completed, send me an e-mail with the report. All projects must be completed by **June 30, 2020**.

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

FP1. External force observers for the NAO
FP2. Push recovery for humanoid robots
FP3. Humanoid robot control via hybrid zero dynamics
FP4. Gait generation via MPC for the virtual-mass-ellipsoid Inverted Pendulum
FP5. Guaranteeing safety for autonomous vehicles via Control Barrier Functions
FP6. Motion planning for mobile manipulators with sampling-based MPC
FP7. Implementation of Riemannian Motion Policies for a bimanual task
FP8. Evaluating the performance of stochastic MPC in an application scenario
FP9. Humanoid gait generation: step timing adjustment
FP10. Parking a drifting vehicle
FP11. Human driving behavior correction based on Dynamic Window
FP12. Graceful posture regulation for unicycle robots
FP13. Control of an autonomous bicycle

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1. External force observers for the NAO

Reconstructing external forces acting on a humanoid is a crucial problem, especially in the context of on-line generation of a dynamically stable gait in the presence of disturbances. The problem becomes harder if the robot is not equipped with force/torque sensors such as the NAO. This project consists in studying and comparing at least two state+disturbance observers which should work while the robot is walking. Simulations on MATLAB and/or DART/Gazebo (C++) must be performed to validate the analysis.

- Stephens, “State Estimation for Force-Controlled Humanoid Balance using Simple Models in the Presence of Modeling Error,” ICRA 2011
- Hawley et al, “Kalman Filter Based Observer for an External Force Applied to Medium-sized Humanoid Robots,” IROS 2018
- Englsberger et al, “Smooth Trajectory Generation and Push-Recovery based on Divergent Component of Motion,” IROS 2017

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2. Push recovery for humanoid robots

A humanoid robot, while operating, can be subject to strong and unexpected perturbations. In these cases the humanoid should be able to reactively perform a footstep adaptation to recover from the external push. This project consists in the implementation and comparison between the push recovery properties of the automatic footstep placement of the IS-MPC with a DCM-based gait generation approach. The simulation platform can be MATLAB, DART or Gazebo.

- Scianca et al, “Intrinsically Stable MPC for Humanoid Gait Generation,” Humanoids 2016
- Englsberger et al, “Smooth Trajectory Generation and Push-Recovery based on Divergent Component of Motion,” IROS 2017
- Shafiee et al, “Online DCM Trajectory Generation for Push Recovery of Torque-Controlled Humanoid Robots,” Humanoids 2019

3. Humanoid robot control via hybrid zero dynamics

The aim of this project is to simulate a controlled humanoid in the sagittal plane using the hybrid zero dynamics. A hybrid system is a system whose dynamics are given by multiple sets of differential equations. These govern the evolution of the system in different subsets of the state space, and a set of discrete rules describes how to switch from one differential equation to another. Hybrid systems are commonly used to model systems with contacts, with the time of contact itself determining the transition between two different continuous dynamic representations. A humanoid robot is well described as a hybrid system, as it achieves locomotion by alternating contacts with the ground. The hybrid zero dynamics is an extension of the classic concept of zero dynamics (the maximal internal dynamics of the system that are compatible with the output being identically zero) to the case of hybrid system, and can be used to design a controller for a humanoid robot. The simulation platform will be MATLAB (the robot model is available).

- Westervelt et al, "Hybrid Zero Dynamics of Planar Biped Walkers," IEEE Transactions on Robotics, 2003
- Westervelt, Ph.D. thesis
- additional material at http://web.eecs.umich.edu/~grizzle/westervelt_thesis/

4. Gait generation via MPC for the virtual-mass-ellipsoid Inverted Pendulum

Model Predictive Control (MPC) is often used to generate gaits for humanoid robots. MPC computes control actions by solving at each step a constrained optimization problem. To achieve real-time implementation on a humanoid robot, the model is usually simplified to a Linear Inverted Pendulum (LIP), which is limited to flat ground and neglects the angular momentum around the CoM in order to remove the nonlinear dynamics. The Virtual-mass-ellipsoid Inverted Pendulum Model can be seen as an extension of the LIP, which is capable of generating vertical motions, and includes the angular momentum by modeling it as a ellipse-shaped mass attached to the CoM. The aim of the project is to implement an MPC control of a Virtual-mass-ellipsoid Inverted Pendulum Model in MATLAB. The starting point will be the Intrinsically Stable MPC scheme, which uses the LIP model, and will be provided in the form of a MATLAB code.

- Guan et al, "Push Recovery by Angular Momentum Control during 3D Bipedal Walking Based on Virtual-mass-ellipsoid Inverted Pendulum Model," Humanoids 2019
- Scianca et al, "MPC for Humanoid Gait Generation:Stability and Feasibility", 2019

5. Guaranteeing safety for autonomous vehicles via Control Barrier Functions

Control Barrier Functions have been recently introduced as a tool for formulating safety-related constraints for optimization-based controllers, where performance-related constraints are formulated through Control Lyapunov Functions. Such approach has been used in many fields, ranging from biped locomotion to multi-robot systems. The aim of this project is to implement an optimization-based controller that allows an autonomous vehicle (modeled as a unicycle) to achieve performance objectives (e.g., path tracking, desired velocity,...) as much as possible, while simultaneously guaranteeing safety objectives (e.g., lane keeping, adaptive speed regulation). MATLAB or V-REP simulations in different scenarios are required.

- Ames at al, "Control Barrier Functions: Theory and Applications," 2019 ECC
- Xu et al, "Realizing Simultaneous Lane Keeping and Adaptive Speed Regulation on Accessible Mobile Robot Testbeds," 2017 CCTA

6. Motion planning for mobile manipulators with sampling-based MPC

The aim of this project is to investigate the use of sampling-based MPC to solve the motion planning problem for a mobile manipulator. In contrast to classic MPC, sampling-based MPC replaces numerical optimization with a procedure that selects of the best among the branches of a tree which is generated in the prediction horizon by sampling. As a prediction model, the mobile manipulator's dynamic model will be used. First, given the kinematic and dynamic characteristics of a planar mobile manipulator, a dynamic model must to be created. Then, a sampling-based MPC algorithm should be implemented and tested in MATLAB.

- Brooks et al, "Randomised MPC-based Motion Planning for Mobile Robot Obstacle Avoidance," in ICRA 2009

7. Implementation of Riemannian Motion Policies for a bimanual task

The objective of this project is to study a novel motor control framework called Riemannian Motion Policies (RMP) for a bimanual task in simulation. RMPs are represented as a second-order dynamical systems (acceleration field or motion policy) coupled with a corresponding Riemannian metric. The motion policy maps positions and velocities to accelerations, while the metric captures the directions in the space important to the policy. Students are required to study the basics of motion primitives, to become familiar with the RMP method and to implement the corresponding framework. This project can be developed both in MATLAB or C++.

- Ratliff et al, "Riemannian Motion Policies," 2018
- Ijspeert et al, "Dynamical Movement Primitives: Learning Attractor Models for Motor Behaviors," Neural Computation 2013
- Paraschos et al, "Probabilistic Movement Primitives," NIPS 2013

8. Evaluating the performance of stochastic MPC in an application scenario

This project is aimed at studying stochastic MPC methods and their use in robotic scenarios. A C++ software package that implements a stochastic MPC method is available and should be analyzed. The students should propose and carry out the application of the method to a robotic system of interest in the AMR course.

http://cse.lab.imtlucca.it/~bemporad/teaching/mpc/imt/7-stochastic_mpc.pdf
Kouzoupis, "Structure-exploiting Numerical Methods for Tree-sparse Optimal Control Problems," 2019
https://github.com/dkouzoup/treeQP/tree/master/treeqp/src

9. Humanoid gait generation: step timing adjustment

Step adjustment for humanoid robots improves robustness in gaits. The aim of the project is to evaluate a method which allows a simultaneous variation of the step length and duration and compare it with a heuristic approach used in our lab. A first result is the direct implementation of the two strategies in MATLAB on the LIP model of the humanoid. A further possible development would be a dynamic simulation in V-REP.

- Khadiv et al, "Step Timing Adjustment: A Step toward Generating Robust Gaits," Humanoids 2016

10. Parking a drifting vehicle

Conventional models for wheeled mobile robots assume no-slipping and no-skidding conditions, leading to nonholonomic path/trajectory planning. However, in some practical situations (e.g., high-speed motions) slipping and skidding cannot be ignored or can even be useful. To this end, it is important to model the friction force between the tire and the contact plane. The objective of this project is formulate a drift parking problem and to implement a solution strategy that combines a nonholonomic planner with a controller for the drifting mode. The performance of the strategy should be tested in MATLAB.

- Morinaga et al, "Motion Planning of Drifting Vehicle with Friction Model Considering Nonholonomic Constraint," ICRA 2015

11. Human driving behavior correction based on Dynamic Window

The objective of this project is to study a safety driving methodology for human drivers based on Dynamic Window Approach (DWA), as an implementation of Advanced Driving Assist Systems (ADASs). Human driving behaviors are embedded in the design of the controller. The resulting control inputs are then limited and corrected by using DWA as an obstacle avoidance strategy. Results of trajectory following and obstacle avoidance using the proposed method should be compared with a baseline visual servoing controller. Implementation platform is V-REP.

- Kang et al, "An approach of human driving behavior correction based on Dynamic Window Approach," 2014 IEEE Intelligent Vehicles

12. Graceful posture regulation for unicycle robots

The objective of this project is to study a feedback controller for solving the posture regulation problem in unicycle-like robots. The controller uses a polar coordinate system moving with the vehicle and includes a slow subsystem which describes the position of the vehicle, where the reference orientation is obtained via state feedback, and a fast subsystem which describes the steering of the vehicle, where the vehicle heading is exponentially stabilized to the obtained reference orientation. A path following strategy based on the proposed control law can be used to satisfy velocity, acceleration and jerk bounds imposed by the user. The performance of this controller should be compared with the classical posture regulation controller that uses a fixed polar coordinate system. Implementation platform is MATLAB.

- Park and Kuipers, “A Smooth Control Law for Graceful Motion of Differential Wheeled Mobile Robots in 2D Environment,” 2014 ICRA

13. Control of an autonomous bicycle

The objective of this project is to study the dynamics of bicycles from the perspective of control. Models of different complexity are possible, starting with simple ones and ending with more realistic models generated from multibody software. Of particular interest are models that capture essential behavior such as self-stabilization as well as models that demonstrate difficulties with rear wheel steering. Students are expected to implement and compare two or more controllers through MATLAB simulations.

- Åström et al, “Bicycle dynamics and control,” Control Systems Magazine 2005