

# Autonomous Navigation for Mobile Robots in Crowded Environments

## Challenges with ground and aerial robots

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### Abstract

The large diffusion of service robots in our life requires safe and efficient autonomous navigation in human environments. In particular, navigation in a crowded environment is a challenge, because the robot motion could compromise human safety.

This Ph.D. dissertation focuses on two different scenarios: with aerial and ground robots, respectively.

The first scenario focuses on safe navigation for Unmanned Aerial Systems (UASs) in urban areas. It is a critical scenario, because an impact of the UAS on the ground may cause casualties. To solve this problem, a novel approach is proposed, where a risk-based map and a risk-aware path planning strategy are used to determine a safe flight mission.

The risk-based map quantifies the risk of flying over an urban area, defining areas where the flight is allowed or not, because of no-fly zones or high risk. The risk is defined with a probabilistic risk assessment approach and by combining several layers with information about population density, sheltering factor, obstacles at the flight altitude and coverage of the mobile network used to connect the UAS with the ground.

Hence, a risk-aware path planning searches for a minimum risk path to reach a desired target position in the map and considering the risk-based map. In particular, the proposed risk-aware path planning strategy consists of two phases. First, an offline path planning searches for the globally optimal path based on a static risk-based map. Then, an online path planning updates the path according to a dynamic risk-based map. In this thesis, two different risk-aware path planning strategies are proposed: *(i)* using riskA\* and Borderland algorithms, able to provide an offline and an online path planning, respectively; and *(ii)* with riskRRT<sup>X</sup>, a path planning and re-planning algorithm used to perform both offline and online phases.

A simulation of a flight operation over a city is performed, demonstrating how the proposed approach is able to compute and maintain a safe flight mission, even in densely populated areas.

The definition and the implementation of a safe navigation for UASs in urban areas is the main contribution of this thesis. In particular, the risk-based map is a novel tool used to plan safe flight missions. Hence, both path planner algorithms are novel solutions, specifically designed to work with the risk-based map and minimize the risk to the population on the ground.

The proposed approach relies on a Cloud-based framework that enables intelligent navigation of UASs in urban environments, as well as manage and coordinate a fleet of UASs in the low altitude airspace. Thanks to mobile technologies, the UAS is connected with the ground with unprecedented opportunities, enabling Cloud technologies to be used with UASs. The proposed framework is another contribution of this thesis, designed to propose a reference architecture for autonomous UASs in urban areas.

On the other hand, the second scenario focuses on the autonomous navigation of ground robots in crowded environments. Unlike aerial robots, ground robots operate directly in an environment occupied by humans, requiring a safe and comfortable motion among people. The aim is to implement safe autonomous navigation to offer service robotics applications. For this purpose, a Cloud-based architecture for generic service robotics applications is presented. Thanks to Cloud technologies and the concept of Cloud Robotics, most of the intelligence resides on the Cloud. Only some essential elements to control the vehicle, manage the hardware and provide safety are installed aboard the robot. Such elements would guarantee the safe accomplishment of basic actions to maintain the safety toward people.

In particular, a dynamic path planner is proposed, able to compute and update a safe and valid path in highly dynamic environments, solving the so-called *freezing robot problem*. The path planner continuously checks, repairs and updates the current path, in order to always have a valid path to be executed by the robot.

Hence, a novel motion controller is presented, called Particle Filter Model Predictive Equilibrium Point Control (PF-MPEPC). It comprises a Model Predictive Control method combined with the Equilibrium Point approach. PF-MPEPC determines an optimal trajectory of the robot toward the goal pose, avoiding obstacles with a smooth motion. Particle Filters in the prediction phase take into account uncertainties, such as measurement noise and disturbances.

Both the dynamic path planner and the motion controller are contributions of this thesis. The aim is the implementation of autonomous navigation strategies for service robots. For this purpose, two service robotics applications are described: *(i)* the robot Courier, a service robot in a workspace, which welcomes and escorts new visitors to the desired venue in an office environment, and *(ii)* Virgil, a service robot in a museum. Both service robotics applications demonstrate the effectiveness of the proposed Cloud-based architecture for service robots.