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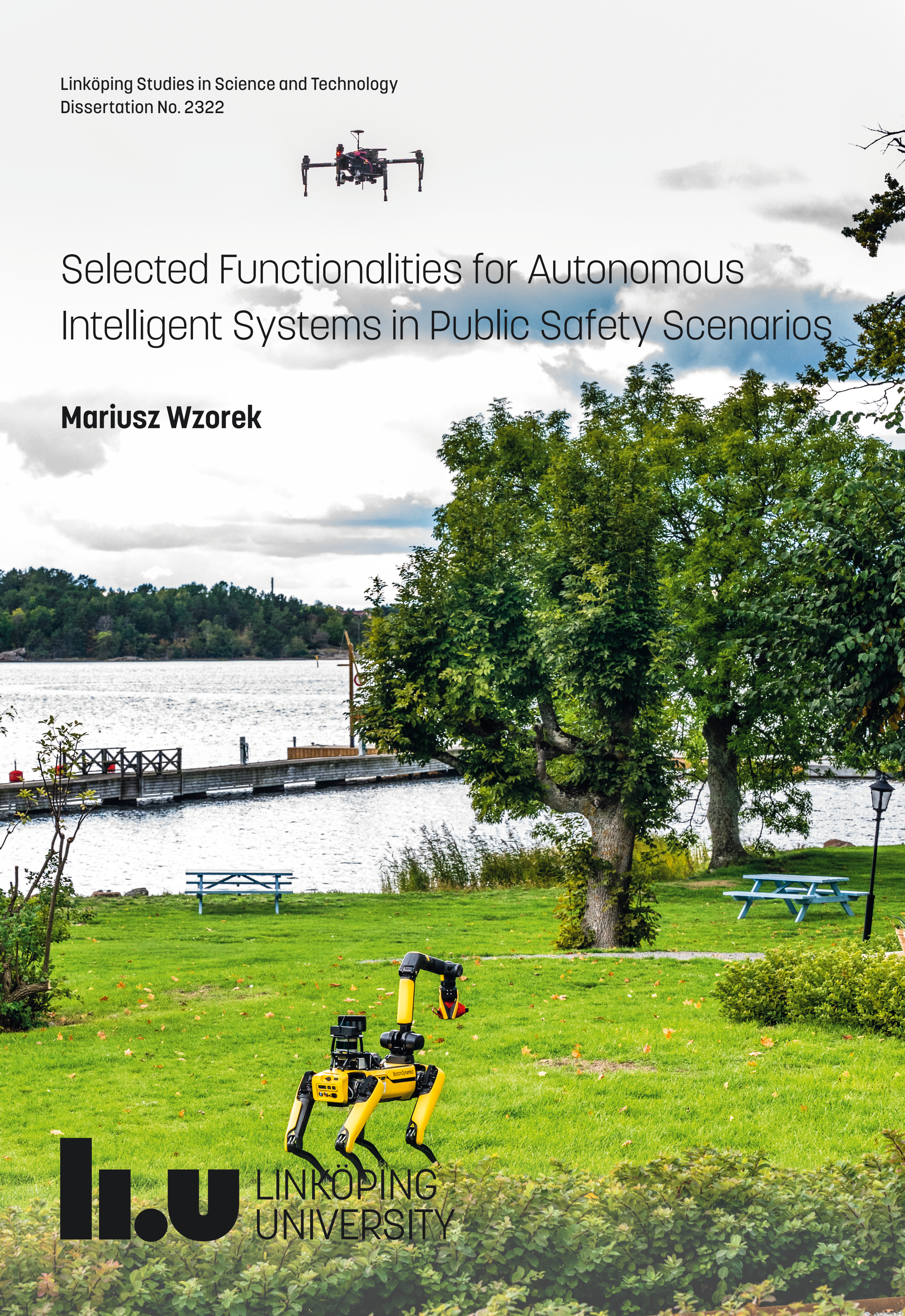
Selected Functionalities for Autonomous Intelligent Systems in Public Safety Scenarios

Mariusz Wzorek



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Selected Functionalities for Autonomous Intelligent Systems in Public Safety Scenarios

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Photos on covers show autonomous intelligent systems developed by the AIICS division at Linköping University during field test experimentation and demonstrations conducted at the WASP WARA-Public Safety Arena in Gränsö, Sweden (2019, 2022). Photos: Thor Balkhed, Linköping University.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Teknik som använder artificiell intelligens (AI) används överallt i dagens samhälle och spelar en viktig roll i det dagliga livet. Röstassistenter som Siri och Alexa, robotdammsugare och självkörande bilar är exempel på framgångsrika tillämpningar av AI som har fått stort genomslag. Tillämpningarna av artificiell intelligens är dock mer mångsidiga och sträcker sig långt utöver personligt bruk eller användning i hemmet. En viktig tillämpningsdomän som väsentligt bidrar till samhällets välbefinnande är allmän säkerhet (eng public safety). Inom ramen för denna applikationsdomän har statliga och icke-statliga myndigheter, såsom blåljusorganisationer (till exempel polis eller brandkår), ofta i uppdrag att utföra viktiga livräddande aktiviteter när de hanterar konsekvenserna av naturkatastrofer eller katastrofer som orsakats av naturen eller människor, såsom jordbävningar, översvämningar, orkaner eller oljeutsläpp.

De senaste framstegen inom AI och robotik erbjuder nya verktyg som räddningspersonal kan använda för att förkorta svarstiderna och göra räddningsinsatser mer effektiva. Dessa verktyg inkluderar autonoma intelligenta system, såsom markrobotar eller obemannade flygfarkoster (UAV, ofta kallade drönare). Moderna räddningsteam har börjat använda dessa system i sin verksamhet, men att integrera dem i verksamheten är inte trivialt. Ett exempel på detta är när man använde markrobotar och UAV:er vid åtgärderna man vidtog i samband med kärnkraftsincidenten orsakad av jordbävningen i Fukushima, Japan, 2011. Även om många kommersiella system redan finns tillgängliga på marknaden och används i faktiska fall, finns det fortfarande många viktiga forskningsfrågor som måste behandlas. Det gäller till exempel design och utveckling av autonoma intelligenta system för att öka deras autonomi och effektivt göra dessa system lättare att använda. Dessutom måste man också överväga hur dessa system kan användas inom allmän säkerhet.

Denna avhandling presenterar en samling av funktionaliteter/metoder för autonoma intelligenta system i scenarion för allmän säkerhet. Avhandlingen är uppdelad i två delar. I del 1 är fokuset på hur man kan integrera olika AI-tekniker som krävs för att lösa problemet med autonom navigering i dynamiska eller föränderliga miljöer. Detta är en väsentlig förmåga som alla intelligenta robotsystem bör ha för effektiv användning i verkliga tillämpningar. Att lösa navigeringsproblemet är inte trivialt och kräver att man kombinerar komponenter från olika forskningsområden, såsom rörelseplanering, reglerteknik och perception. Rörelseplanerare hanterar det svåra problemet med att beräkna användbara kollisionsfria vägar baserat på information som inkluderar statiska kartor och uppgifter om dynamiska hinder. Kontrollalgoritmer används för att följa planerade vägar och se till att roboten följer vägar exakt. Perception omfattar processer som används för att bland annat uppskatta eller bygga kartor baserade på sensoriska data som en planerare sedan kan använda. Genom att kombinera dessa tekniker kan vi bygga system som gör det möjligt för ett robotsystem att navigera självständigt i dynamiska eller föränderliga miljöer. I avhandlingen presenteras designen av ett navigeringsramverk som används på UAV-system som kombinerar de nödvändiga funktionerna som behövs på ett nytt sätt för att lösa navigationsuppgifter effektivt.

I del 2 koncentrerar vi oss på en viktig tjänst som autonoma intelligenta system kan erbjuda till räddningsteam. Ett av de problem som räddningsteam möter i de inledande faserna av ett uppdrag är att få tillgång till effektiv kommunikation. I efterdyningarna av en katastrof, är befintlig kommunikationsinfrastruktur ofta inte fullt fungerande eller till och med obefintlig. I denna avhandling behandlas problemet med att använda heterogena team av UAV:er för att distribuera kommunikationsnoder som används för att etablera ad hoc Wireless Mesh Networks (WMN). I avhandlingen presenteras en design med tillhörande prototyp av kommunikationsnoder bestående av små batteridrivna enheter som inkluderar routrar och kan levereras autonomt av UAV:er. Avhandlingen behandlar också några grundläggande problem som finns i samband med beräkning av optimala nodplaceringar som är nödvändiga för framgångsrika distributioner av WMN. Effektiva nya algoritmer för att lösa dessa problem föreslås.

Stora ansträngningar har lagts på att tillämpa de utvecklade teknikerna i verkliga system och scenarier. Därmed har tillvägagångssätten som presenteras i denna avhandling validerats genom omfattande simuleringar och, ännu viktigare, verkliga experiment med olika UAV-system. Flera bidrag som presenteras i avhandlingen är generiska och kan anpassas till andra autonoma intelligenta systemtyper och andra tillämpningsdomäner.

ABSTRACT

The public safety and security application domain is an important research area that provides great benefits to society. Within this application domain, governmental and non-governmental agencies, such as blue light organizations (e.g., police or firefighters), are often tasked with essential life-saving activities when responding to fallouts of natural or man-made disasters, such as earthquakes, floods, or hurricanes.

Recent technological advances in artificial intelligence and robotics offer novel tools that first responder teams can use to shorten response times and improve the effectiveness of rescue efforts. Modern first responder teams are increasingly being supported by autonomous intelligent systems such as ground robots or Unmanned Aerial Vehicles (UAVs). However, even though many commercial systems are available and used in real deployments, many important research questions still need to be answered. These relate to both autonomous intelligent system design and development in addition to how such systems can be used in the context of public safety applications.

This thesis presents a collection of functionalities for autonomous intelligent systems in public safety scenarios. Contributions in this thesis are divided into two parts. In Part 1, we focus on the design of navigation frameworks for UAVs for solving the problem of autonomous navigation in dynamic or changing environments. In particular, we present several novel ideas for integrating motion planning, control, and perception functionalities within robotic architectures to solve navigation tasks efficiently.

In Part 2, we concentrate on an important service that autonomous intelligent systems can offer to first responder teams. Specifically, we focus on base functionalities required for UAV-based rapid ad hoc communication infrastructure deployment in the initial phases of rescue operations. The main idea is to use heterogeneous teams of UAVs to deploy communication nodes that include routers and are used to establish ad hoc Wireless Mesh Networks (WMNs). We consider fundamental problems related to WMN network design, such as calculating node placements, and propose efficient novel algorithms to solve these problems.

Considerable effort has been put into applying the developed techniques in real systems and scenarios. Thus, the approaches presented in this thesis have been validated through extensive simulations and real-world experimentation with various UAV systems. Several contributions presented in the thesis are generic and can be adapted to other autonomous intelligent system types and application domains other than public safety and security.

This work has been supported by the ELLIIT Network Organization for Information and Communication Technology, Sweden (Project B09), and Wallenberg AI, Autonomous Systems and Software Program (WASP) funded by the Knut and Alice Wallenberg Foundation, in addition to the sources already acknowledged in the individual papers.

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Mariusz Wzorek
Linköping, May 2023

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Chapter

1 Introduction

Unmanned Aircraft Vehicles (UAVs) are growing in popularity and are used in a wide range of applications. Due to their mobility, they offer fast response times and can provide data from a bird's-eye-view perspective, making them unique among other robotic systems. The UAV technology is mature, and aircraft with different propulsion system configurations offering a wide range of payload capacities and endurance are available commercially. However, most of these systems have limited autonomous capabilities, and an operator typically has to perform a fair share of work manually. To increase the efficiency of use and deployment of UAV systems in real application scenarios, researchers are actively working on various aspects of autonomous functionalities related to these systems. The desired level of autonomy for unmanned aircraft may vary depending on the type of mission being executed, where certain missions need to be controlled in some detail by a ground operator while others should preferably be fully autonomous. Nevertheless, automation is almost always desirable for some aspects of a mission.

The work presented in this thesis is divided into two parts. In Part I, we focus on the base functionalities required in the UAV systems to autonomously and safely navigate in dynamically changing environments. This is an essential capability of a UAV system required for successful practical deployment in any real mission scenario. Part II focuses on autonomous services UAVs can offer in emergency response operations. In particular, we investigate possibilities of the use of UAVs for the autonomous deployment of ad-hoc communication networks, which can be used by rescue teams on the ground and are crucial in the first phases of any rescue operation [127].

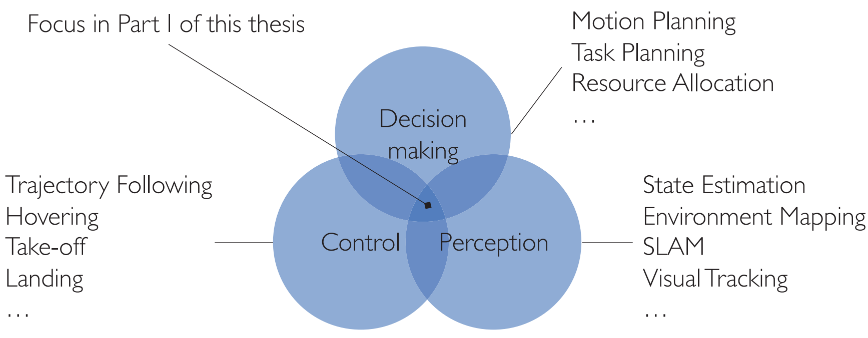


Figure 1.1: Conceptual overview of processes involved in solving the navigation problem in the UAV domain.

1.1 Problem Definition

Generally, in any autonomous robotics system, one can distinguish functionalities dealing with various aspects of a task at hand. Figure 1.1 presents one standard classification of the processes involved divided into three conceptual components: decision-making, control, and perception. In the context of navigation, the decision-making processes typically include a set of algorithms related to solving more complex tasks including, but not limited to, the calculation of optimal collision-free plans based on the environment models. A set of control functions implementing different operational modes provide an interface to the hardware components. The role of each such control mode is to generate control signals to meet a well-defined control objective. Last but not least are the perception processes which include a set of algorithms responsible for creating models based on sensory data that both control and decision-making processes can use.

Functionalities in all categories have different complexities resulting in different timing requirements. For example, the control processes require fast update rates to react promptly to perceived changes in the vehicle's state and changes in the environment. Path or motion planners require considerable computational time since they typically solve inherently intractable search problems. Integrating these components with different timing requirements is not trivial, especially if the system should safely navigate in dynamic environments that include moving obstacles. Additionally, one needs to consider the computational power available onboard the vehicle. While larger UAV systems can typically carry heavy payloads (e.g. powerful computers), including high computational capabilities in smaller UAVs pose a problem. In Part I of this thesis, we focus on the efficient integration of processes involved in the safe navigation task as well as consider the problem of limited computational power on small-scale UAVs. For this purpose, the following general (RQ1) and more specific (RQ1.1-1.3) **Research Questions** are formulated:

RQ1 How to efficiently integrate motion planning algorithms, control, and perception functionalities within UAV software architectures to solve the problem of autonomous safe navigation in dynamic or changing environments?

- **RQ1.1** How to extend the use of existing motion planning techniques for dynamic or changing environments?
- **RQ1.2** How to integrate motion planning with low-level control and perception?
- **RQ1.3** As the UAVs scale down in size, how can one leverage advances in low-power, small-size electronic components to allow onboard execution of computationally intensive algorithms?

Part II of the thesis focuses on services which a team of heterogeneous robots can offer within the emergency rescue application domain. In recent decades there has been an increasing occurrence of natural disasters [3] that include wildfires, hurricanes, earthquakes, and floods. Furthermore, these events are expected to grow in number as an effect of human-induced climate change [66]. State-of-the-art emergency response is required to minimize loss of life and property damage. Consequently, supporting the efforts of disaster relief teams with intelligent heterogeneous robotic assistants has been an active research topic with many examples of successful deployments [38, 100, 110].

One of the significant problems the rescue teams face is the need for more reliable and resilient communication means, which are essential for the efficient coordination and planning of their operations. Unfortunately, in the aftermath of natural or man-made disasters, the existing communication infrastructures are either partially or entirely inoperable. Among many technological solutions that can be used to alleviate communication problems, ad-hoc wireless networks are a new promising technology as they are easy to deploy and cost-effective. In that context, the problem considered in Part II of this thesis focuses on the base functionalities required for UAV-based rapid deployment of ad-hoc communication infrastructures in the initial phases of rescue operations. An overview of the mission scenario associated with these functionalities is presented in Figure 1.2.

The following general (RQ2) and specific (RQ2.1-2.3) **Research questions** related to Part II of the thesis are formulated:

RQ2 How can UAVs be utilized to rapidly deploy ad-hoc communication networks in emergency rescue scenarios?

- **RQ2.1** What are the requirements for designing UAV-deployable communication nodes that can be used to establish an ad-hoc communication network?
- **RQ2.2** What practical constraints should be considered in communication node placement problems?
- **RQ2.3** How can one efficiently solve communication node placement problems?

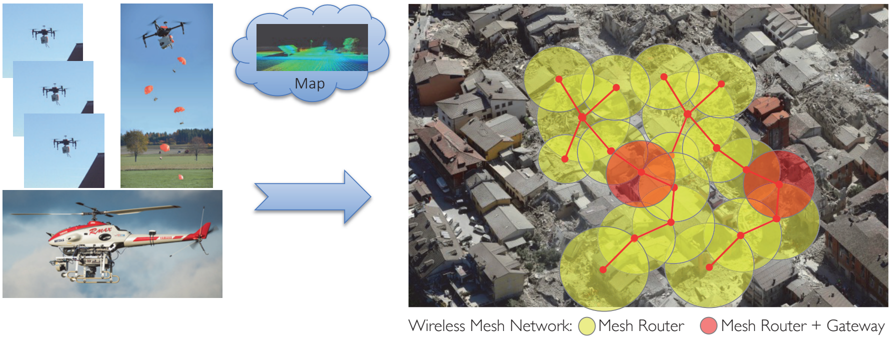


Figure 1.2: An overview of the mission scenario considered in Part II of the thesis.

1.2 Methodology

The research presented in this thesis was conducted within a field robotics group at the Artificial Intelligence and Integrated Computer Systems Division (AIICS) at Linköping University. Conceptually, the contributions presented in the thesis include a combination of theoretical, engineering (prototyping), and real-world deployment activities. As such, the work has been driven by several application scenarios where the goal was to develop a theoretical basis for the proposed solutions, implement them in software and/or hardware, and evaluate them in real-world deployments. The adopted approach used a theory-prototyping-deployment feedback loop. The experimental evaluation results of the deployed systems often led to new and challenging theoretical and engineering problems that needed to be solved.

The UAV systems used for prototyping and real-world evaluations are presented in Figure 1.3. These include UAVs of different flight configurations, payloads, and sizes:

1. the Yamaha RMAX helicopter platform (3.6 m in length, powered by a 21 hp two-stroke engine with a maximum takeoff weight of 95 kg).

2. the LinkMAV, a small coaxial UAV (50 cm in rotor diameter with a maximum takeoff weight of 0.9 kg).

3. the LinkQuad quadrotor system (70 cm tip-to-tip in diameter with a maximum takeoff weight of 1.4 kg).

4. the DJI Matrice 100 quadrotor [1] (1 m tip-to-tip in diameter with a maximum takeoff weight of 3.6 kg).

All the platforms are part of the UAV fleet developed at AIICS division at Linköping University (LiU), Sweden. The Yamaha RMAX and DJI Matrice 100 UAVs are commercial platforms augmented with custom sensory and computational payloads [4,

[1] www.dji.com/se/matrice100

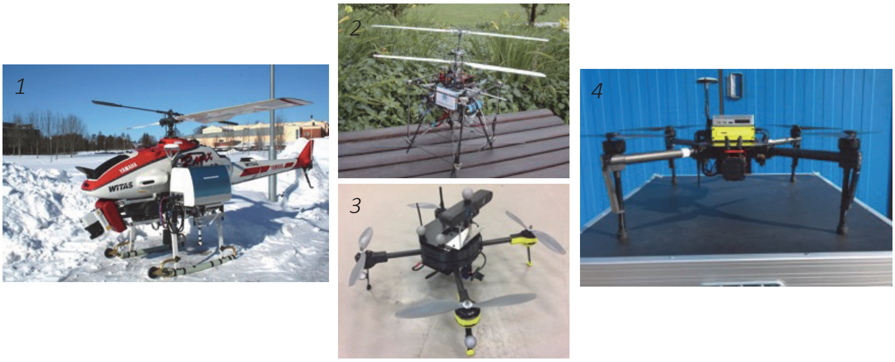


Figure 1.3: Experimental UAV platforms used for evaluation of the proposed approaches in the thesis.

45], while the LinkMAV and the LinkQuad UAV systems have been developed in-house [47, 132].

Application scenarios considered in Part I drove the design of software frameworks for UAV platforms of different sizes and computational capabilities to solve the navigation problem in indoor and outdoor environments. To address the research questions, we propose models of navigation frameworks represented as state machines that combine motion planners, control modes, and perception functionalities. The frameworks were implemented and evaluated in simulations and real flights.

In Part II, the application scenario led to the development of physical devices that can be deployed from UAVs and serve as communication nodes in ad-hoc wireless mesh networks. The actual experimentation with UAV-deployed networks resulted in defining a new mathematical model for the router node placement problem. The problem has also been considered in combination with a gateway placement problem. Several algorithms have been proposed, implemented, and evaluated to solve both problems efficiently. Theoretical results included complexity and convergence analysis of the algorithms to determine their scalability and other features. The extensive empirical analysis focused on showing how the algorithms scale to real-world application scenarios. The problems were based on real GIS environment models of large sizes up to several square kilometers.

1.3 Brief Outline of Contributions

Publications included in this thesis include seven peer-reviewed articles, and one article in preparation for journal submission. Figure 1.4 presents an overview of the publications with associated research questions.

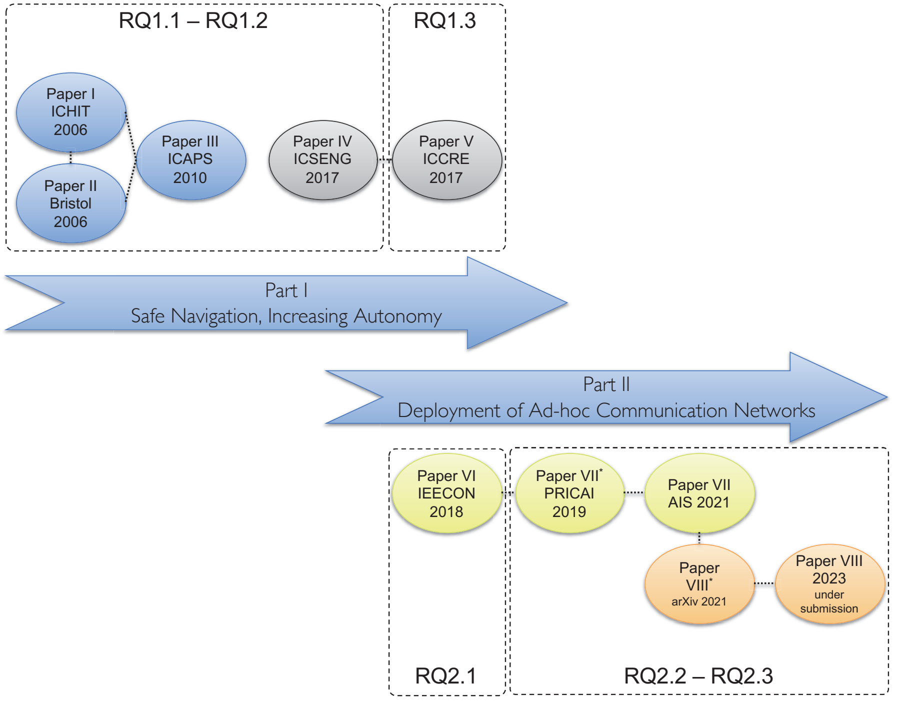


Figure 1.4: Overview of the published articles included in the thesis and their relation to the specific research questions.

Paper I Mariusz Wzorek and Patrick Doherty. "Reconfigurable Path Planning for an Autonomous Unmanned Aerial Vehicle." In: *Proceedings of the International Conference on Hybrid Information Technology.* Vol. 2. IEEE. 2006, pp. 242–249.

This publication presents a novel idea of dynamic replanning where path planning techniques are used to either repair or generate a new plan when the currently executed path is no longer valid due to occlusions. A navigation framework that combines path planners with a path following control mode is defined, implemented, and evaluated using the Yamaha RMAX UAV system with hardware-in-the-loop simulations.

Paper II Mariusz Wzorek, Gianpaolo Conte, Piotr Rudol, Torsten Merz, Simone Duranti, and Patrick Doherty. "From Motion Planning to Control – A Navigation Framework for an Unmanned Aerial Vehicle." In: *Proceedings of the 21st Bristol International Conference on UAV Systems.* 2006, pp. 1–8.

In this publication, the framework presented in Paper I is described in the context of a hybrid deliberative/reactive software architecture developed for the Yamaha RMAX UAV platforms [45]. Here details of the dynamic path following control mode [31] used in combination with the path planners are presented, among other aspects of the system. An example of real-world mission execution where the UAV dynamically replans paths to avoid added no-fly zones is presented.

Paper III Mariusz Wzorek, Jonas Kvarnström, and Patrick Doherty. "Choosing Path Replanning Strategies for Unmanned Aircraft Systems." In: *Proceedings of the International Conference on Automated Planning and Scheduling.* Vol. 20. 1. 2010, pp. 193–200.

The framework presented in Papers I-II is extended with a selection mechanism for the most optimal choice of available replan/repair strategies. First, we apply machine learning techniques to build a set of predictors to estimate how much time a particular replanning strategy would take and its outcome in terms of optimality. Then, the predictors are used to select the best available replanning strategy given the available time (i.e. estimated time to collision).

Paper IV Mariusz Wzorek, Cyrille Berger, and Patrick Doherty. "A Framework for Safe Navigation of Unmanned Aerial Vehicles in Unknown Environments." In: *Proceedings of the 25th International Conference on Systems Engineering.* IEEE. 2017, pp. 11–20.

The work presented in Papers I-III focused on a single platform and did not include a perception component. In contrast, in this publication, we propose to combine sample-based motion planning techniques with an Optimal Reciprocal Collision Avoidance (ORCA) [14] reactive controller and 3D environment mapping functionalities. The proposed navigation framework allows for dynamic collision avoidance with static and other cooperating robotic platforms in unknown environments. The presented system has been deployed on the LinkQuad UAV and evaluated both in simulation and in real flights.

Paper V Mariusz Wzorek, Piotr Rudol, Gianpaolo Conte, and Patrick Doherty. "LinkBoard: Advanced Flight Control System for Micro Unmanned Aerial Vehicles." In: *Proceedings of the International Conference on Control and Robotics Engineering.* IEEE. 2017, pp. 102–108.

This publication presents the design, development, and evaluation of an advanced flight control system, the LinkBoard. The system has been used in experimentation presented in Paper IV, among other research publications. Additionally, the LinkBoard has been integrated with the coaxial LinkMAV [47] platform, which contributed to scoring third place in the IMAV 2007 international competition[2] in the indoor challenge category.

Paper VI Mariusz Wzorek, Cyrille Berger, Piotr Rudol, and Patrick Doherty. "Deployment of Ad Hoc Network Nodes Using UAVs for Search and Rescue Missions." In: *Proceedings of the International Electrical Engineering Congress.* IEEE. 2018, pp. 1–4.

[2] `http://www.imavs.org/2007/`

This publication presents the design and development of communication nodes that can be used for setting up ad-hoc communication networks in emergency rescue scenarios. The node includes a mesh router, battery, Raspberry Pi, GPS/IMU, and a parachute system. Two node prototypes were constructed and evaluated in field experiments.

Paper VII Mariusz Wzorek, Cyrille Berger, and Patrick Doherty. "Router and Gateway Node Placement in Wireless Mesh Networks for Emergency Rescue Scenarios." In: *Autonomous Intelligent Systems.* 1.1, 2021, pp. 1–30.

This journal article presents a number of contributions related to the rapid deployment of ad-hoc communication networks in emergency scenarios using UAVs. We define a new extended router node placement problem and propose an efficient heuristic-based algorithm for solving it. The algorithm is evaluated empirically and compared to other state-of-the-art solutions. Additionally, we propose and evaluate two alternative algorithms for solving the combined router and gateway node placement problems. The paper is an extension of two previous conference publications: Paper VI and Paper VII* [135].

Paper VIII Mariusz Wzorek, Cyrille Berger, and Patrick Doherty. "Polygon Area Decomposition Using a Compactness Metric." In: *under journal submission.* 2023.

In this journal article, we extend the definition of the *area partitioning problem* which deals with dividing polygonal areas into a set of disjoint sub-regions with predefined area sizes. The extended problem aims at maximizing the compactness metrics of each sub-region. We propose and evaluate an efficient algorithm for solving the new problem. Generally, by imposing the shape constraints, the algorithm avoids generating sub-regions with sharp corners. This is an essential feature exploited in the router and gateway node placement algorithm presented in Paper VII. Additionally, the new problem and the algorithm have applications to terrain covering in the UAV domain and GIS-related problems dealing with zoning or redistricting.

1.4 Additional Publications

This section lists peer-reviewed publications that were not included in the thesis but are relevant to the topics discussed.

1. Mariusz Wzorek, David Landén, and Patrick Doherty. "GSM Technology as a Communication Media for an Autonomous Unmanned Aerial Vehicle." In: *Proceedings of the 21st Bristol International UAV Systems Conference*. 2006, pp. 1–15

2. Torsten Merz, Piotr Rudol, and Mariusz Wzorek. “Control System Framework for Autonomous Robots Based on Extended State Machines.” In: *Proceedings of the International Conference on Autonomic and Autonomous Systems*. IEEE. 2006, pp. 14–14.

3. Simone Duranti, Gianpaolo Conte, David Lundström, Piotr Rudol, Mariusz Wzorek, and Patrick Doherty. “LinkMAV, a Prototype Rotary Wing Micro Aerial Vehicle.” In: *Proceedings of the 17th IFAC Symposium on Automatic Control in Aerospace*. 2007, pp. 473–478.

4. Piotr Rudol, Mariusz Wzorek, Gianpaolo Conte, and Patrick Doherty. “Micro Unmanned Aerial Vehicle Visual Servoing for Cooperative Indoor Exploration.” In: *Proceedings of the IEEE Aerospace Conference*. IEEE. 2008, pp. 1–10.

5. Gianpaolo Conte, Maria Hempel, Piotr Rudol, David Lundström, Simone Duranti, Mariusz Wzorek, and Patrick Doherty. “High Accuracy Ground Target Geo-Location Using Autonomous Micro Aerial Vehicle Platforms.” In: *Proceedings of the AIAA Guidance, Navigation, and Control Conference*. Vol. 26. 2008, p. 6668.

6. Piotr Rudol, Mariusz Wzorek, and Patrick Doherty. “Vision-based Pose Estimation for Autonomous Indoor Navigation of Micro-scale Unmanned Aircraft Systems.” In: *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2010, pp. 1913–1920.

7. Gianpaolo Conte, Alexander Kleiner, Piotr Rudol, Karol Korwel, Mariusz Wzorek, and Patrick Doherty. “Performance Evaluation of a Light Weight Multi-Echo Lidar for Unmanned Rotorcraft Applications.” In: *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* 40 2013, pp. 1–6.

8. Patrick Doherty, Jonas Kvarnström, Mariusz Wzorek, Piotr Rudol, Fredrik Heintz, and Gianpaolo Conte. “HDRC3 - A Distributed Hybrid Deliberative/Reactive Architecture for Unmanned Aircraft Systems.” In: *Handbook of Unmanned Aerial Vehicles*. 2014, pp. 849–952.

9. Martin Danelljan, Fahad Shahbaz Khan, Michael Felsberg, Karl Granström, Fredrik Heintz, Piotr Rudol, Mariusz Wzorek, Jonas Kvarnström, and Patrick Doherty. “A Low-Level Active Vision Framework for Collaborative Unmanned Aircraft Systems.” In: *Computer Vision - ECCV 2014 Workshops. Lecture Notes in Computer Science*. Vol. 8925. 2015, pp. 223–237.

10. Olov Andersson, Mariusz Wzorek, Piotr Rudol, and Patrick Doherty. “Model-Predictive Control with Stochastic Collision Avoidance using Bayesian Policy Optimization.” In: *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2016, pp. 4597–4604.

11. Patrick Doherty, Jonas Kvarnström, Piotr Rudol, Mariusz Wzorek, Gianpaolo Conte, Cyrille Berger, Timo Hinzmann, and Thomas Stastny. "A Collaborative Framework for 3D Mapping Using Unmanned Aerial Vehicles." In: *International Conference on Principles and Practice of Multi-Agent Systems*. Springer. 2016, pp. 110–130.
12. Cyrille Berger, Piotr Rudol, Mariusz Wzorek, and Alexander Kleiner. "Evaluation of Reactive Obstacle Avoidance Algorithms for a Quadcopter." In: *Proceedings of the International Conference on Control, Automation, Robotics and Vision (ICARCV)*. IEEE. 2016, pp. 1–6.
13. Cyrille Berger, Mariusz Wzorek, Jonas Kvarnström, Gianpaolo Conte, Patrick Doherty, and Alexander Eriksson. "Area Coverage with Heterogeneous UAVs using Scan Patterns." In: *Proceedings of the International Symposium on Safety, Security and Rescue Robotics*. IEEE. 2016, pp. 342–349.
14. Olov Andersson, Mariusz Wzorek, and Patrick Doherty. "Deep Learning Quadcopter Control via Risk-Aware Active Learning." In: *Proceedings of the Thirty-First AAAI Conference on Artificial Intelligence*. Vol. 31. 1. 2017.
15. Timo Hinzmann, Thomas Stastny, Gianpaolo Conte, Patrick Doherty, Piotr Rudol, Mariusz Wzorek, Enric Galceran, Roland Siegwart, and Igor Gilitschenski. "Collaborative 3D Reconstruction Using Heterogeneous UAVs: System and Experiments." In: *Proceedings of the International Symposium on Experimental Robotics*. Springer. 2016, pp. 43–56.
16. Patrick Doherty, Cyrille Berger, Piotr Rudol, and Mariusz Wzorek. "Hastily Formed Knowledge Networks and Distributed Situation Awareness for Collaborative Robotics." In: *Autonomous Intelligent Systems* 1.1 2021, pp. 1–29.
17. Cyrille Berger, Patrick Doherty, Piotr Rudol, and Mariusz Wzorek. "RGS$^{\oplus}$: RDF Graph Synchronization for Collaborative Robotics." In: *Autonomous Agents and Multi-Agent Systems* 2023. Under Review

1.5 Thesis Outline

The remainder of the thesis is structured as follows. In Chapter 2 we consider background information related to the topics of navigation and increasing the autonomy of UAVs. Chapter 3 provides an introduction to contributions dealing with the deployment of ad-hoc communication networks. A summary of contributions and discussion is presented in Chapter 4. Finally, the remainder of the thesis includes the relevant publications.

CHAPTER

2 Autonomous Navigation Frameworks

In a broad sense, *navigation* can be defined as safely traversing the environment from a start to a goal position. Several services related to different aspects of the problem have to be combined and integrated in the robotic system to automate the navigation process. These include functionalities from intertwined and partially overlapping research areas that include, but are not limited to, path or motion planning, control theory, and robotics perception. The problem of autonomous navigation has been extensively studied in different contexts, and the body of work is vast. Therefore, this chapter intends to present the context for the included papers instead of providing an exhaustive literature review.

The navigation problem considered in this thesis focuses on scenarios in which a UAV platform safely and autonomously traverses through static or dynamically changing environments. Traditionally, approaches that solve the problem of navigation in static environments are composed of a motion planner and a controller. Figure 2.1 depicts an overview of a typical navigation system. Motion planners generate collision-free paths given a world-model or map of the environment. Maps provide information about locations of obstacles represented as 2D or 3D geometric structures. Planners use maps by applying collision checking techniques while searching for feasible and collision-free paths. Path representations used by the planners vary depending on the planner design and factors modeled in the planning problem. In the simplest case, a path generated by a planner may consist of a set of waypoints connected with straight lines, disregarding the underlying dynamics of the robotics system, thus making them less feasible for execution. In more advanced cases, paths may be represented as splines with guarantees on continuity of first- and second-order derivatives or even sequences of robot states annotated with time (typically referred to as trajectories). Generally, motion planning problem formulations that account for more factors lead to paths that retain higher feasibility at the price of computation time as the size of the state space in which the planner

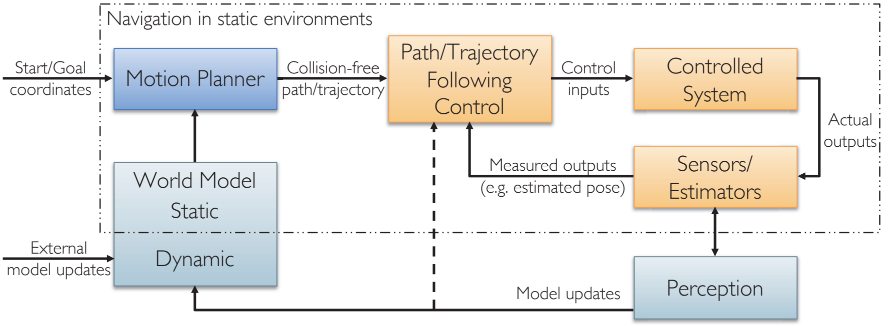


Figure 2.1: Example navigation system overview.

operates increases. Motion planners are often referred to as *global* planners as they commonly take into account all obstacles present in a map and aim at finding globally optimal paths according to pre-defined criteria, for example, shortest path or lowest energy consumption.

The role of Path Following Controllers (PFCs) is to execute given paths using a feedback-loop scheme by generating a series of control inputs. The type of control inputs calculated depends on the platform configuration (e.g. helicopter, multirotor, or fixed-wing) where typically the PFC provides desired positions, velocities, or attitude angle targets to a low-level control system implemented in the platform. The PFC uses the robot's state (e.g. pose) estimated from sensor measurements as feedback to follow the path as closely as possible. Perhaps the most common approach for state estimation in the UAV domain is the Extended Kalman Filter (EKF) [92, 95]. Typically, the filter combines measurements from several sensors, such as accelerometers, gyroscopes, pressure gauges, and a GPS.

Navigation systems that assume static environments have limited usability in real-world applications. The world changes continuously, maps of the environments can be outdated or non-existent, and robots should be able to navigate in environments populated with human operators. Therefore, it is essential for a robotic system to be able to navigate autonomously in unknown or partially known environments that include dynamic obstacles. Incorporating a dynamic collision-avoidance ability in the navigation system is a much more complex problem that poses additional challenges. For example, the internal model of the environment (i.e. the map) has to be created and continuously updated as the UAV navigates throughout the environment (Figure 2.1, bottom). This is done by integrating perception processes, which address problems such as mapping, obstacle detection and tracking, or even object recognition. Information derived by these functionalities is based on onboard sensors such as cameras, stereo-vision systems, LiDARs (laser imaging, detection, and ranging), structured-light sensors, sonars, etc. Additionally, the navigation system has to monitor its path execution and react to any perceived contingencies that arise during navigation to ensure a collision-free path is always executed.

Various approaches have been proposed in the literature to deal with these challenges, which can be categorized into two groups. The first group includes techniques based on reactive collision-avoidance modes, realized using various underlying approaches, for example, optimization, force-field, or sense-and-avoid. In the context of system design presented in Figure 2.1, these algorithms can be viewed as specialized path following controllers that, in addition to a reference path or trajectory, take as an input the sensory data (i.e. model updates) continuously provided by perception functionalities. Generally, the reactive modes tend to be computationally efficient, thus meeting the computational constraints of the computer systems integrated onboard UAVs and reacting quickly to newly perceived obstacles. However, they are typically local in nature, i.e. consider only local changes in the environment, often limited to the sensor range. Thus, navigation systems built solely based on this principle exhibit sub-optimal performance, where executed paths include unnecessary detours and suffer from the problem of local minima. Examples of such solutions include algorithms capable of generating dynamic collision avoidance maneuvers based on sensory data [65, 69, 113, 121].

The second group includes the systems that combine global motion planners with adequate path following controllers (including the reactive modes). These techniques often use motion planners with various replanning or plan repair strategies that aim at generating globally optimal paths, which are continuously executed by path following controllers. Examples of such systems where lattice-based or sampling-based motion planning techniques are integrated include [5, 36, 90, 94, 103, 106], in addition to the work presented in this thesis.

The main contributions included in Part I of the thesis focus on system integration, where two variants of navigation frameworks combining motion planning, path following control, or reactive modes and perception are developed and evaluated.

The remainder of this chapter is structured as follows. First, we discuss each essential part of a navigation system separately, starting with path and motion planning, followed by path following control and perception. Then, we focus on navigation frameworks that combine these functionalities into systems that can solve navigation tasks in dynamic and changing environments.

2.1 Path and Motion Planning

Path and motion planning algorithms deal with the problem of generating collision-free paths or motions for a robot in order to navigate in an environment. The physical space in which the robot navigates, called the workspace $\mathcal{W}$, is most often modeled as $\mathcal{R}^3$ but can be restricted to $\mathcal{R}^2$ for robots navigating in a single plane (e.g. car-like robots in a 2D flat environment). This type of representation is particularly well-suited for collision checking since the robot, and the obstacles are represented in the same space. However, the workspace representation is inadequate in many practical applications to describe the planning problem fully. Thus, a more expressive representation is required.

The *configuration space* (*C* or *C-space*) is defined as a vector space or manifold of robot configurations q, where a configuration is a set of parameters that uniquely defines the location of all points of the robot in the workspace $\mathcal{W}$. For a rigid-body robot such as a UAV platform this would include not only its position but also its orientation. Additionally, not all robot configurations are attainable due to obstacle constraints. The *free space* or C_{free} is a subset of the C-space of a robot that is free from collisions with obstacles.

When dealing with robotic systems in motion, the configuration of the robot is insufficient to describe the problem: The dynamic state of a robot (i.e. velocity) has to be accounted for. The *state space* representation extends the configuration space by adding first-order derivatives $\dot{q}$ of the robot configuration q. Thus, for a robot configuration $q = (q_0, \ldots, q_n)$, the state x is defined by $x = \langle q, \dot{q} \rangle$ where $\dot{q} = (\dot{q}_0, \ldots, \dot{q}_n)^T$. As an implication, for an n-dimensional C-space, the state space X is a 2n-dimensional differentiable manifold.

In addition to the requirement of avoiding collisions, plans must also satisfy *kinematic* and *dynamic* constraints. Kinematic constraints include only first-order derivatives of the configuration parameters, while second-order derivatives such as acceleration are allowed in the dynamic constraints. Both of these types of constraints belong to a class of non-holonomic constraints (also called motion constraints) and are common for many types of robots. A robot is non-holonomic if it has fewer controllable degrees of freedom than total degrees of freedom. A car is non-holonomic since it can only drive forwards or backwards, not sideways. So is a helicopter or a quadrotor platform [50, 91]: Though both can move freely in any direction, their freedom of movement depends on their speed. When a UAV is hovering or flying slowly it could be considered to be holonomic, but this would constrain its usage.

The algorithms used in our frameworks handle the kinematic and dynamic constraints of the UAV platforms by applying a decoupled approach. This is done by combining path planners with path following controllers, where planners generate geometric paths which are then executed by controllers that handle the dynamic constraints of the platforms.

Path Planning

The path planning problem is defined as finding a path in C_{free} that connects the start (q_0) and the goal (q_g) configuration. There are two main classes of motion planning algorithms: combinatorial and sample-based [79]. The problem of finding optimal paths between two robot configurations in a high-dimensional configuration space is intractable in general. Canny and Reif [24] prove that even a simple problem of finding the optimal path for a point-like robot in three-dimensional space with polyhedral obstacles is NP-hard. Another example is presented by Reif and Wang [111] where additionally non-holonomic constraints on the curvature radius are added (e.g. a car-like robot). In this case the problem of finding an optimal path is proven to be NP-hard even for two-dimensional problems.

Combinatorial motion planning uses an exact representation of the original problem (often referred as *exact* algorithms). The algorithms in this class are complete and optimal, but most often computationally impractical for solving real-world problems (i.e. more than 2 dimensions). Sample-based methods use an approximation of the C_{free} continuous space (in configuration space or state-space) in order to deal with the complexity of high-dimensional problems. The discrete representation of the original continuous space (typically represented in the form of a graph) sacrifices strict completeness for a weaker definition such as *resolution completeness* or *probabilistic completeness* [79].

An algorithm is said to be *complete* if, for all problem instances, it returns a solution in a finite amount of time if a solution exists. In sample-based planning, resolution completeness is related to the denseness of the approximation of the C_{free} continuous space. As the number of iterations of the sample-based algorithm goes to infinity, the samples come arbitrarily close to any configuration. A deterministic algorithm that samples the entire C_{free} space densely is said to be resolution complete. Consequently, such an algorithm will find a solution in a finite time if one exists. However, if there is no solution to the problem, it may run forever. Hence, these algorithms do not meet the requirements of strict completeness. Probabilistic completeness is related to random sampling used in most sample-based planners. An algorithm is said to be probabilistically complete if the probability that it finds an existing solution converges to one when the number of samples goes to infinity. The two main sample-based motion planning algorithms are probabilistic roadmaps and rapidly exploring random trees.

Probabilistic Roadmaps

The original probabilistic roadmap (PRM) algorithm developed by Kavraki et al. [73] works in two phases, one offline and the other online. In the offline phase, a discrete roadmap representing a free configuration space (C_{free}) is generated using a 3D world model. First, it randomly generates a number of configurations and checks for collisions with the world model. A local path planner is then used to connect collision-free configurations taking into account the kinematic and dynamic constraints of the robot. Paths between two configurations are also checked for collisions. This results in a roadmap approximating the configuration free space (C_{free}). Figure 2.2 presents an example of the PRM offline phase for a simple 2D environment.

In the online or querying phase, initial and goal configurations are provided, and an attempt is made to connect each configuration to the previously generated roadmap using the local path planner. A graph search algorithm such as A* is then used to find a path from the initial to the goal configuration in the augmented roadmap. Optionally, an additional path optimization can be applied to the generated solution. An example of the PRM online phase for a simple 2D environment is presented in Figure 2.3.

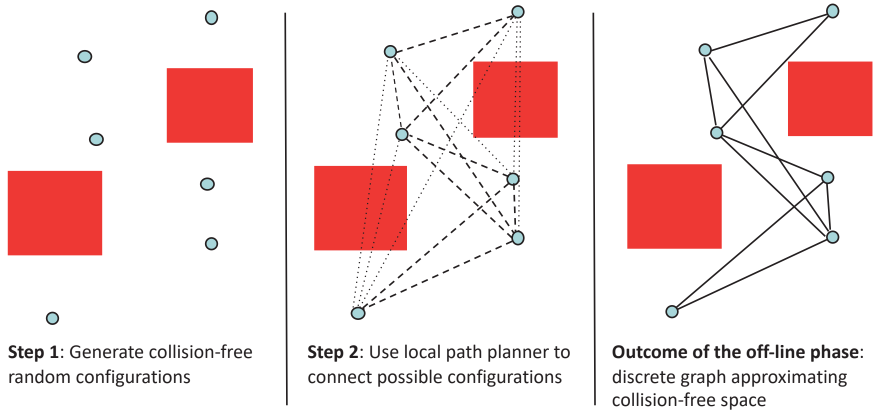


Figure 2.2: Example PRM roadmap generation (offline phase) for a simple 2D environment.

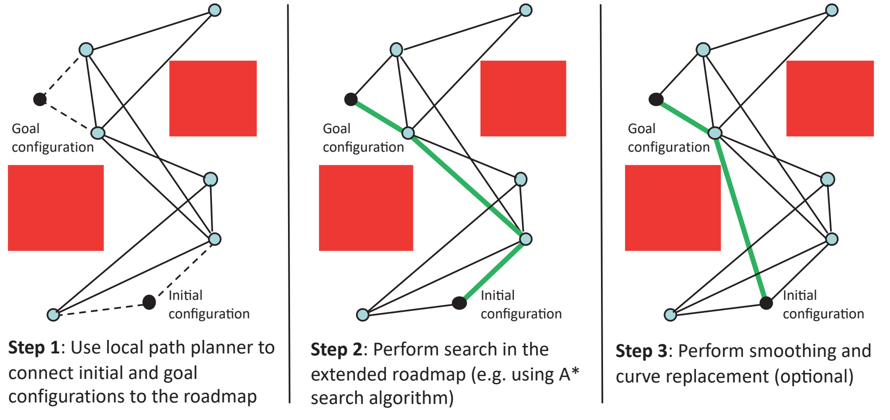


Figure 2.3: An example of the PRM online phase for a simple 2D environment.

Since its inception, many improvements and extensions to the original PRM algorithm has been proposed in the literature. Perhaps the most notable works include LazyPRM [20] and PRM* [72].

Rapidly Exploring Random Trees

The rapidly exploring random tree (RRT) [77, 80] algorithm is a variant of the sample-based algorithm that does not use a precompiled roadmap in contrast to the PRM planner. Instead, it uses a specialized search strategy to construct a roadmap online rather than offline to find solutions quickly during runtime. This is a strong advantage of the RRT algorithm since it does not require knowing a 3D model of the

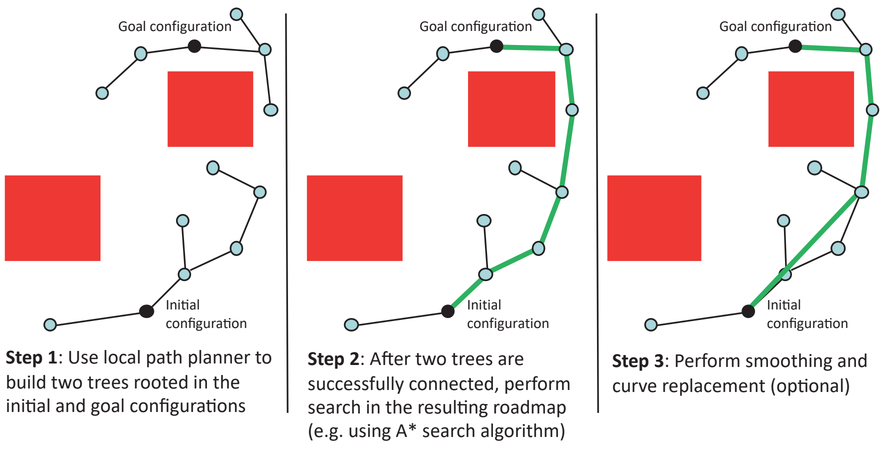


Figure 2.4: RRT path plan generation.

environment beforehand. It makes it directly applicable for dynamic and unknown environments.

The algorithm generates two trees rooted in the start and end configurations respectively, by exploring the configuration space randomly from both directions. While the trees are being generated, attempts are made at predefined intervals to connect them to create one roadmap. After the roadmap is created, the remaining steps in the algorithm are the same as with PRMs.

Figure 2.4 presents an example of RRT execution in a simple 2D environment. Note that the resulting plan is not optimal or as high quality as in the case of the PRM planner. It can happen that even after applying a post processing path optimization step (e.g. removal of redundant configurations) the result can contain detours. In the case of our simple 2D example (Figure 2.4), the tree expansion from the goal node can grow either left or right of the top-right obstacle since the exploration is random. Additionally, each time the planner is executed with the same start and goal configurations, generated plans will most certainly be different, as opposed to the PRM with a fixed precompiled roadmap. An extended version of the algorithm, called RRT*, has been proposed by Karaman et al. [72] to address this problem. The RRT* is provably asymptotically optimal such that the algorithm generates solutions that converge almost surely to the optimum as the number of samples increases.

Path Planner Extensions

The PRM and RRT planners integrated within our navigation approach (Papers I-IV) are presented in Figure 2.5. Planners use an Oriented Bounding Box Trees (OBB-Trees) algorithm [56] for collision checking and an A* algorithm for graph search. Here one can optimize for various criteria such as shortest path, minimal energy usage, etc.

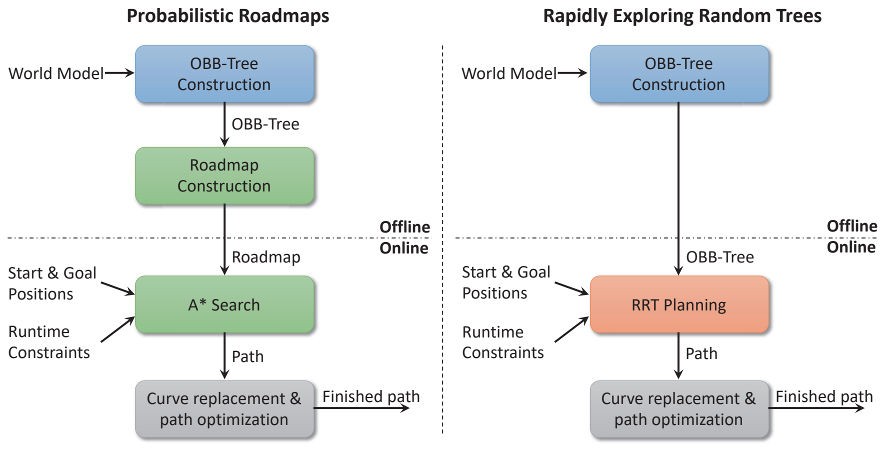


Figure 2.5: PRM and RRT path plan generation.

The standard PRM and RRT algorithms are formulated for fully controllable systems only (i.e. holonomic). This assumption is valid for a helicopter or a quadrotor UAV flying at low speeds with the capability to stop and hover at each waypoint. However, when the speed is increased, the UAV can no longer negotiate turns of a smaller radius, which imposes demands on the planner similar to non-holonomic constraints for car-like robots.

The most straightforward way of handling dynamic constraints in the PRM and RRT algorithms is to complement the configurations with their derivatives and record the complete state at each node in the graph. This enables the local path planner to adapt the path between two nodes to their associated derivatives, which is necessary to respect the dynamic constraints at boundary points between adjacent edges in the solution path. However, this approach significantly increases the complexity of the problem as the dimensionality of the space in which the roadmap/tree is situated is doubled. An alternative approach to non-holonomic planning is to postpone handling of the non-holonomic constraints to the runtime phase. The following extensions have therefore been made concerning the standard version of the PRM and RRT algorithms.

Multi-level roadmap/tree planning This extension has been inspired by a multi-level planner proposed by Sekhavat et al. [119] and it is used in our PRM and RRT planners [45, 105]. In this approach, linear paths are first used to connect configurations in the graph/tree. Later, these are optimized and improved by a combination of post-processing techniques to generate smooth paths represented by cubic curves. The techniques implemented in our method include curve replacement, node alignment and elimination.

Figure 2.6 depicts the process of replacing linear path segments with cubic curves. These are required for smooth high speed flight. If it is impossible to re-

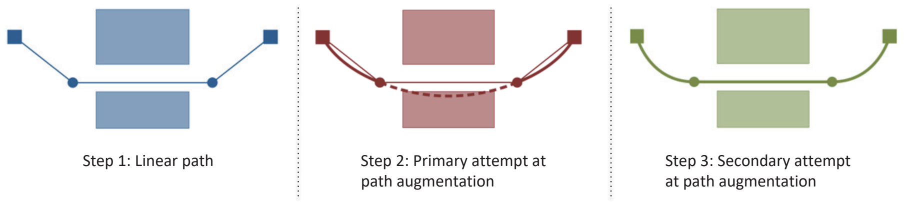


Figure 2.6: Transformation from linear to cubic path segments for smooth flight.

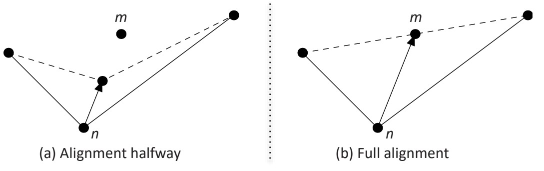


Figure 2.7: Alignment of nodes for improved path quality.

place a linear path segment with a cubic curve then the UAV has to slow down and switch to hovering mode at the connecting waypoint before continuing. However, this rarely happens in practice.

The PRM and RRT algorithms rely on random sampling when creating roadmaps/trees approximating the free space. Additionally, these approximations are limited in density. Thus, depending on the planner configuration the paths generated by the algorithms may be jagged or irregular. In order to improve the quality of the paths, two additional smoothing steps are applied:

- Node Alignment: For each node n along the path, two attempts are made to move it to a point that straightens out the path (Figure 2.7). The point m in the middle between the two neighbors is located. First, an attempt is made to move n halfway to m (Figure 2.7a), if this is possible given known obstacles. Then an attempt is made to move it all the way to m (Figure 2.7b).

- Node Elimination: For each node along the path, an attempt is made to eliminate it by connecting the two adjacent nodes directly. If the connection satisfies all constraints, the middle node is eliminated.

The curve replacement step described above is performed between the alignment and the elimination step.

Runtime constraint handling The PRM and RRT motion planners have also been extended to deal with additional constraints at runtime that are unavailable during roadmap/tree construction. Such constraints can be introduced during a query for a path plan. The following runtime constraints, handled during the A* search phase, have been introduced:

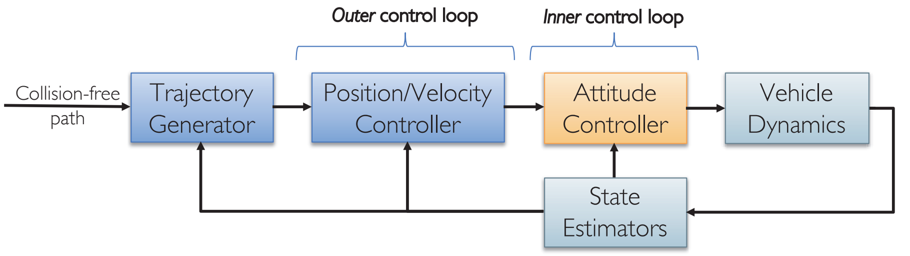


Figure 2.8: A cascade control scheme design applied to the problem of path following for a VTOL UAV.

- Maximum and minimum altitude - verification done through intersection test between the configuration or curve and a horizontal plane.
- Limits on the ascent and descent rates.
- Forbidden regions (no-fly zones) - regions created by a set of horizontal polygons covering an area which the UAV must not enter. The test for configurations is done by checking if a configuration projected in the X/Y plane is within the polygon. The test for curves involves checking for intersections between a curve and any of the planes bounding the polygon in 3D-space.

2.2 Path Following Control

Path or trajectory following problem deals with the execution of paths or trajectories generated by motion planners. The main objective of the control mode designed to solve the problem is to follow a given path or trajectory as close as possible to minimize the tracking error, as generated paths are guaranteed to be collision-free in relation to the world model used during the planning process.

Commonly this problem is approached by designing a cascade control scheme where two levels of feedback control loops are used. The cascade controller design allows for dealing adequately with different time scales of aircraft dynamics exhibited by both VTOL and fixed-wing UAV platform configurations (e.g. [31, 60, 70, 131]). Figure 2.8 depicts an overview of a path following controller for a VTOL UAV. In this case, a fast *inner* feedback control loop is applied to stabilize the vehicle's attitude by generating aircraft actuator commands. A relatively slower process of following a reference path or trajectory is handled by an *outer* feedback controller, which takes as an input a series of positions and/or reference velocities along the path.

Generally, one can distinguish three classes of control approaches used for the design of inner and outer control loops [75]. The first one includes systems based on linear controllers, for example:

- Proportional-Integral-Derivative (PID), e.g. [22, 31];

- H_∞, e.g. [30, 117];
- Linear–Quadratic Regulator (LQR), e.g. [18, 22].

The second category uses model-based nonlinear approaches, for example:

- model predictive control (MPC), e.g. [70, 122];
- adaptive control, e.g. [67].

The final set of approaches uses machine learning techniques, for example:

- fuzzy logic, e.g. [51, 124];
- human-based learning, e.g. [55];
- neural networks, e.g. [109].

As discussed earlier, motion planners may generate both paths and trajectories which consider additional kinematic and dynamic constraints that depend on the particular planning problem formulation. If the planner is designed to generate a trajectory, i.e. a sequence of vehicle states in time, the outer control loop can be designed to execute it directly. Otherwise, an additional control strategy has to be applied to derive positions and velocities which become target states input to the outer controller.

In this thesis, we focus on the latter approach, i.e. a path-following approach, where the problem of generation and execution of a state-space trajectory is handled in two parts. First, path planners generate collision-free paths in the space domain, disregarding time. Second, a path following controller strategy is used to generate a series of reference positions and velocities which are then executed by an outer control loop. Such a separation simplifies the motion planning problem as the state space dimensionality is reduced, thus reducing the planning times. Additionally, the control mode prioritizes closely following the geometrical path with a given velocity, as the UAV platform is not required to be at a certain point at a specific time.

Our navigation frameworks utilize two types of path following controllers. Specifically, in Papers I-III, our method uses the Dynamic Path Following (DPF) control mode presented in detail in [31] with a shorter description also included in Paper II. The DPF mode uses a trajectory generation scheme based on a *virtual leader* approach, similar to the work described in [49]. The generator calculates reference control points along the path, executed by the outer loop implemented using PID controllers, including feed-forward terms to enhance the tracking precision. The DPF controller deployed on a real UAV system (i.e. Yamaha RMax platform) has been shown to exhibit good tracking performance even in windy conditions. It does not, however, directly deal with avoidance of newly detected obstacles generated externally or by perception functionalities.

Consequently, in Paper IV, we investigate an alternative path-following method more suited to handling dynamic obstacles. We integrate a reactive mode based on the Optimal Reciprocal Collision Avoidance (ORCA) algorithm. The algorithm was first proposed by Berg et al. [14] to address the navigation problem for multiple robots operating in a shared environment. The approach has been since applied to navigation problems involving multiple UAVs [2]. The algorithm works in velocity space. Each robot uses relative position and velocity to independently and simulta-

Figure 2.9: Examples of sensors integrated with UAV systems developed at AIICS, LiU. **Top**: Yamaha RMAX UAV with SICK LiDAR, color and thermal cameras mounted below. **Bottom-left**: DJI Matrice 600 with Velodyne LiDAR, and color camera mounted below. **Bottom-right**: LinkQuad UAV with structured-light sensor (top mount), and color camera (bottom mount).

neously select a new velocity to ensure collision-free navigation for at least a preset amount of time. In our framework we use a simple trajectory generation scheme where paths generated by motion planners are sampled along the path at specified distances and the resulting positions are used as sub-goals for execution by the ORCA-based reactive mode. The velocity commands calculated by the reactive controller are executed with a cascade of PID controllers, which implement the outer and inner control loops.

2.3 Perception

Sensor measurements are the primary source of information used by perception functionalities. Sensor types commonly used in robotic applications can be categorized into two groups, depending on the underlying physical principles of how the information is gathered: *active* and *passive*. As the name suggests, active sensors emit energy into the environment and measure properties (e.g. intensity, frequency shift, time of flight) of the reflected, refracted, or scattered beam. These sensors typically offer more accurate measurements while being more expensive than their passive counterparts. Examples of active sensors used in the UAV domain include LiDAR, radar (radio detection and ranging), sonars, and structured-light sensors. Passive sensors work on the principle of measuring energy already present in the environment, for example, emitted by artifacts or reflected energy from natural or artificial sources (i.e. lights or the sun). These sensors are typically lightweight and inexpensive, which makes them perfect candidates for the use onboard UAV platforms. However, the passive sensors' performance is inferior to the active ones since the data measurements are typically noisier and less accurate. Passive sensors commonly used onboard UAVs include color and thermal cameras, and stereo-vision systems, accelerometers, gyroscopes, and GPS receivers. Figure 2.9 presents examples of active and passive sensors integrated with UAV systems used for experimental validation of the proposed approaches.

Generally, the term perception in robotics is used in many contexts. In navigation, however, it commonly relates to two problems: localization and map building. The localization problem deals with estimating the robot's pose in the environment, which is essential for the execution of navigation tasks. Map building or the mapping problem relates to the creation of world models or maps that include static or dynamic obstacles and can be used, for example, by motion planners. Simultaneous Localization and Mapping (SLAM, [48]) techniques address a combination of both problems. Comprehensive surveys of methods proposed in the literature related to mapping, localization and SLAM in the UAV domain can be found in [34, 58, 101]. At AIICS/LiU, we have worked on various problems related to perception in the context of UAVs using both passive and active sensors. For example, work presented in [116] focused on vision-based pose estimation to solve the problem of indoor navigation for small-scale UAVs (MAVs). A collaborative approach to the pose estimation problem has been proposed in [115]. It allows a MAV to navigate in indoor environments in cooperation with a ground robot. Extensive work has been done to investigate the use of LiDAR sensors for mapping using UAVs [33, 44, 63].

The main focus of the work related to perception included in the thesis is on the problem of mapping using range data. In this context, the localization is assumed to be provided either by external tracking systems such as VICON[1] (in indoor cases) or estimators which combine onboard inertial sensors with GPS (in outdoor cases). Range data, or point clouds, represented as a discrete set of data points in space, can be generated using a number of sensors and techniques. These include structured-light depth cameras, laser range finders, stereo vision systems or monocular structure from motion techniques, to name the most commonly used ones. In this work we focused on using a depth camera as the main source of range data. Structured-light sensors provide depth information by projecting a known pattern in the environment using, for example, infrared wavelengths. The depth information is calculated by measuring the difference between the known pattern and its perceived reflection. Sensors of this type are characterized by low weight, low power consumption, and fast update rate and are well suited for use on small-scale UAVs.

[1] www.vicon.com/software/tracker

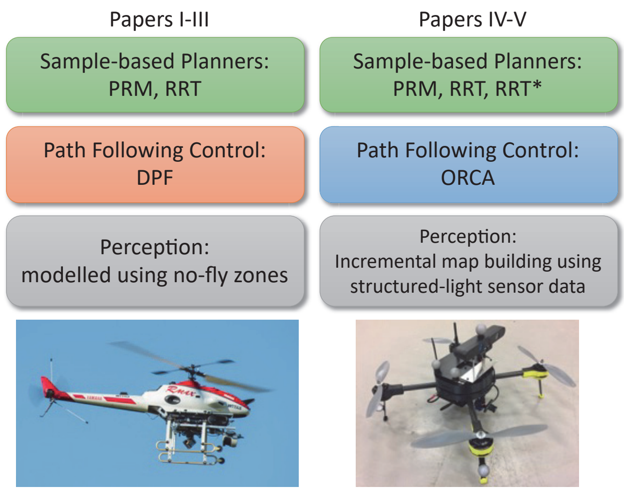


Figure 2.10: Proposed navigation frameworks and their components.

In Paper IV, we approach the problem of mapping by using a depth camera to incrementally build a map during navigation tasks in unknown indoor environments. One of the contributions presented in the paper includes efficient integration of newly acquired sensor data with a collision-checker algorithm. Generally, during the planning process, a considerable amount of collision checks are performed. Therefore, efficient data structures that allow for fast map updates and adequate integration of these structures with collision-checking algorithms are critical aspects of the system design that will influence its general performance.

The framework proposed uses an octree-based 3D map structure, the OctoMap [64], to represent the perceived environment. The OctoMap is an open-source framework suitable for efficient map representation widely used in robotics. It uses probabilistic occupancy estimation, which makes it suitable for incorporating noisy sensor data. The 3D map is built incrementally based on information about the environment in the form of point clouds. Although the OctoMap representation can be used for collision checking, it is less efficient than dedicated collision-checking algorithms, such as OBBTrees. For example, the OBBTree algorithm can efficiently check (analytically) for collisions of entire segments defined as polynomial curves, which our planners use. Therefore, our framework also updates the internal OBBTree data structures (OBBs) in areas where new information is perceived, which can then be used efficiently during planning and dynamic plan repair.

2.4 Navigation Frameworks: Integration Perspective

An essential aspect of any integrated system design is how the different functional components are combined. In this context, a significant effort in Part I of the thesis was put into integration aspects of different navigation system components to successfully apply them to solve navigation tasks in dynamically changing environments. We propose two frameworks that combine motion planners, trajectory following controllers, and perception and deploy them on two UAV systems operating in indoor and outdoor environments. Figure 2.10 presents an overview of the frameworks and their components.

In Papers I-III, we focus on integrating two sample-based motion planners based on PRM and RRT algorithms with the DPF controller and propose a novel path execution mechanism. The mechanism offers an efficient method for the dynamic replanning of a motion plan based on unforeseen contingencies which may arise during the execution of a plan. These contingencies may be based on perceived new obstacles provided by perception functionalities or they may be inserted by an operator in the form of no-fly zones. The latter approach is used in the first navigation framework (Papers I-III).

Commonly, systems that combine motion planners and path following controllers in a collision-avoidance context apply the following path execution scheme. Global planners generate collision-free segmented paths based on current knowledge of the environment (i.e. map). A path following controller executes each segment. When a collision is detected during the execution of the path, a plan repair scheme is applied to generate an updated path taking into account newly detected obstacles. Typical plan repair schemes include using a fixed, incremental or anytime approach. For example, the system proposed by Oleynikova et al. [103] applies a local replanning using optimization (fixed scheme), where the start and goal states for the plan repair are chosen based on the planning time horizon. The approach proposed by Lu et al. [94] performs a full path replanning from the current state to the goal. The system presented by Lin et al. [90] generates incrementally several alternative trajectories based on intermediate points, from which the shortest is chosen. Anytime variants of the RRT algorithm have been proposed by Ferguson et al. [53, 54], where the algorithms incrementally generate improved plans.

Contrary to these techniques, we propose an alternative approach that aims at selecting and executing the best plan repair scheme that yields the best plan based on the amount of time available for collision avoidance. We introduce a concept of a replanning *strategy* that considers two criteria. The first criterion defines a choice of the start and goal states for replanning in relation to the initial path. Figure 2.11 depicts example strategies based on start/goal criterion for a short path consisting of 7 segments. Note that each strategy progressively re-uses more of the initially generated plan, thus cutting down on planning times but potentially producing less optimal plans. The empirical evaluation of these strategies is presented in Paper I.

The second criterion defines which motion planning algorithm and its configuration is selected, as many motion planning methods are also parameterized in various ways. For example, PRM planners generate a roadmap graph in a pre-processing phase and search this graph whenever a plan is required. Increasing the number of nodes in the graph will increase plan quality, but this will also affect the time required for plan generation. Thus, conceptually based on the two criteria, our re-

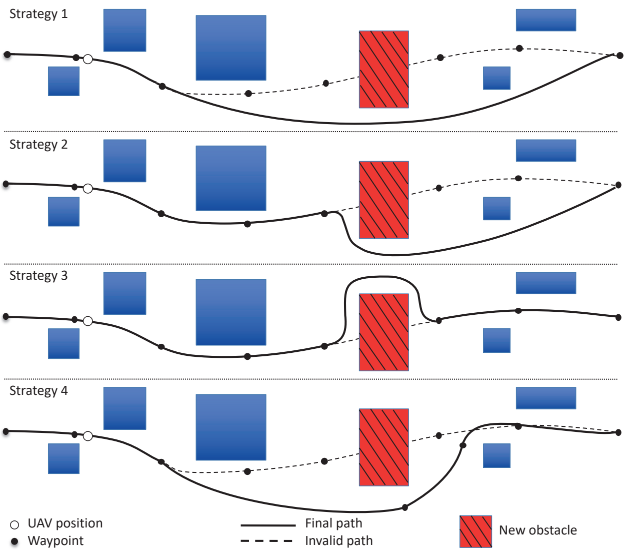


Figure 2.11: Example replanning strategies based on start/goal state selection.

planning *strategy* represents a specific choice of which parts of a path are replanned and which motion planning algorithm and its parameters are selected.

In Papers I-II, we propose and evaluate a navigation framework which includes a path execution mechanism that allows for dynamically applying different replanning strategies during navigation tasks. The framework is integrated with the hybrid deliberative/reactive software architecture developed at AIICS/LiU [45]. Conceptually, the path execution mechanism includes several functional components, and its model can be represented as an augmented state machine. Reactive Task Procedures (TPs, [43]) are used to implement the mechanism. A TP is a high-level procedural execution component that provides a computational mechanism for achieving different robotic behaviors. Figure 2.12 presents the path execution mechanism in the context of the integrated system (left) and its state machine model (right). The three primary functional blocks are highlighted in the figure and represent states and services associated with: 1) segment sequentialization, i.e. execution of path segments (Blue); 2) plan monitoring and estimation of times related to currently executed path segments, including the time available to apply a replanning strategy (Orange); 3) selection and execution of path replanning strategies (Green).

In Paper III, we focus on the problem of choosing the best possible replanning strategy when new obstacles are detected, and a new plan needs to be generated within the available time (i.e. time to collision). The time required for applying a particular strategy and the resulting plan quality (i.e. after the repair) depends on many factors. For example on features of the current plan, the obstructed segment position and size, and the relevant areas of the map. In Paper III, we propose a novel method for the selection problem based on machine learning. For each strategy, a

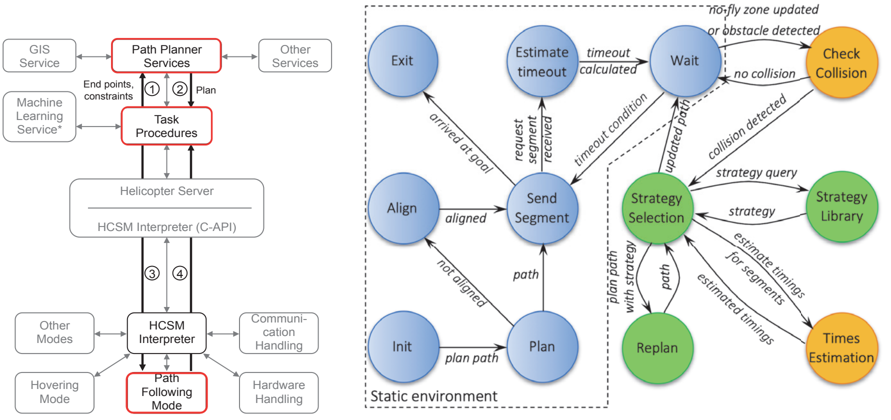


Figure 2.12: Overview of the path execution mechanism implemented in the navigation framework and deployed on the Yamaha RMax UAV. A system integration perspective (left). An augmented state machine model (right). States and services associated with: path execution (Blue), monitoring and times estimations (Orange), selection and execution of path replanning strategies (Green).

set of two prediction models is created using the Support Vector Machines [128, 129] technique. One for estimating the required time for applying the path repair and the other for predicting the expected plan quality. The flight time is used as the quality measure, however, other criteria can be used, for example, fuel or energy consumption. The selection mechanism is tested in two operational environments with different complexity. The empirical evaluation results show that the flight times are improved by up to 25% compared to the use of a fixed replanning strategy, resulting in times close to the best achievable with the available planning algorithms.

In Paper IV, we propose a second framework that integrates sample-based motion planners with a reactive control mode built around the ORCA algorithm deployed on a small-scale UAV (Figure 2.10). Additionally, the framework includes a perception functionality that dynamically updates the world model based on data from a structured-light depth camera. The use of ORCA-based control was previously investigated in the context of navigation problems involving multiple UAVs [2]. The authors proposed an extension to the original algorithm [14] to deal with the static obstacles provided by perception functionalities. The presented solution, however, is solely based on the reactive mode. Hence, it still suffers from the local minima problem since the control signals are generated based on the locally sensed obstacles, and no predictive or planning functionalities are used.

In our work, this problem is alleviated by combining the reactive mode with path planners that generate globally optimal paths considering all the perceived obstacles. Plans generated by path planners are represented as a set of sub-goals and are used as an input to the reactive control mode. The controller is guided by globally optimal plans and makes sure to reactively avoid any collisions with static and

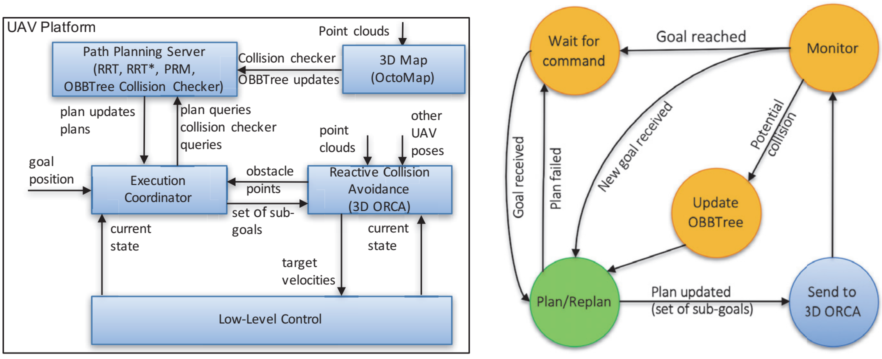


Figure 2.13: Overview of the second navigation framework. A system integration perspective (left). An augmented state machine model (right). States and services associated with: path execution (Blue), monitoring and map updates (Orange), path planning and replanning (Green).

dynamic (e.g. other UAVs) obstacles. This property is especially important when dealing with navigation of multiple UAVs in unknown environments. Figure 2.13 presents an overview of the framework with focus on data flow between the system components (left). On the right of the figure, an augmented state machine system model is depicted. The framework is implemented and validated in simulations and real flight using the LinkQuad MAV platform. The results of experimental evaluations, presented in Paper IV, show the applicability of the approach to the problem of multi-UAV navigation in unknown environments.

Last but not least, we conclude the chapter by discussing contributions related to the development of hardware components used on UAV platforms (Paper V). The frameworks described above combine multiple algorithms and functionalities that require adequate hardware systems to execute on. Generally, a high level of autonomy in any robotic system is achieved by complex software frameworks that include computationally extensive algorithms. Consequently, these software systems often require not one but multiple physical processing units (e.g. CPUs) to ensure the software can be executed in a timely manner. In the context of the UAV domain, larger UAV platforms with larger payloads can carry and use advanced computer systems with considerable computational capabilities, for example, the Yamaha RMax UAV. Small-scale UAVs, however, require specialized flight control systems designed to maximize the available computational power while minimizing their physical dimensions and weight.

In the early days of the MAV development around 2005, the choice of commercially available autopilots was very limited. Therefore, we started a project to develop our own in-house autopilot, called the LinkBoard, suited for MAVs that could support various platform configurations. Paper V presents the final generation of the LinkBoard design, including both the hardware and software aspects. Several open-source and commercial autopilots for small UAVs have been developed in re-

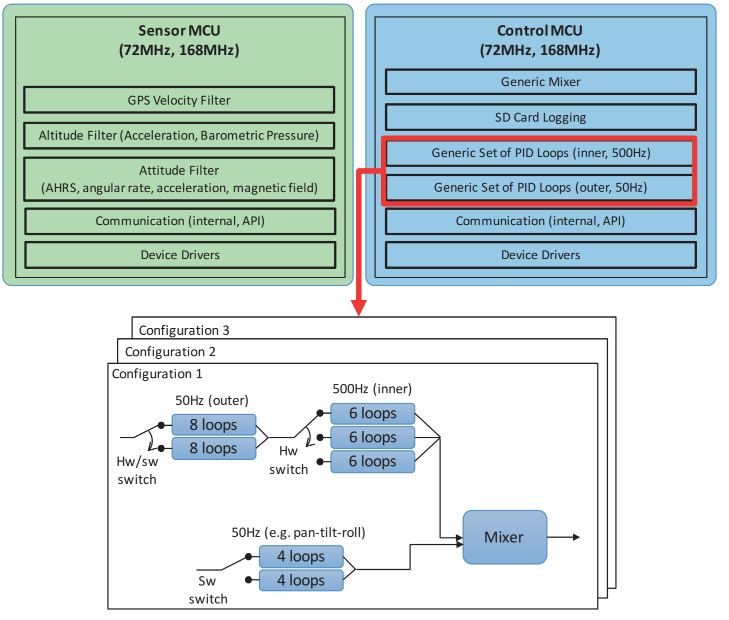


Figure 2.14: Overview of the LinkBoard software architecture distributed over two MCUs with focus on reconfigurable control system.

cent years. Perhaps, the most popular and widely used flight control systems include the PX4/Pixhawk [96] developed at ETH Zurich, and the Paparazzi [23] open-source autopilot project.

The LinkBoard hardware architecture is designed to minimize the autopilot's physical size and weight while maximizing the available computational power. The LinkBoard includes four processing units and a full inertial measurement unit required for implementing autonomous navigation capabilities. Onboard sensors include a three-axis accelerometer, three rate gyroscopes, and absolute as well as differential pressure sensors for estimation of the altitude and the airspeed, respectively. The LinkBoard features several interfaces which allow for easy extension and integration of additional equipment. It supports various external devices (both hardware and software), such as a laser range finder, analog and digital cameras on a gimbal, a GPS receiver, and a magnetometer. The LinkBoard's PCB design is optimized for size and to minimize EMI interference. The autopilot weighs 30g in full configuration and is smaller than the size of a credit card.

The onboard software developed is modular, where configurations of the functional components are stored in the integrated solid-state memory. Such a design is very flexible as it allows for fully reconfiguring the system behavior without the need for recompiling and uploading the firmware. Figure 2.14 presents an overview of the software components distributed over two microcontroller units (MCUs). An example system configuration for a quadrotor platform, the LinkQuad, demonstrating the versatility of the software design is presented in [114], where different high-level flight behaviors are achieved through the parametrization of flight commands implemented onboard the LinkBoard. This integrated system is also used in the context of the second navigation framework (Paper IV), where we utilize the reconfigurable control system for trajectory execution. Both the inner and outer control loops are realized using a cascade of PID controllers.

Due to the available onboard computational power, the LinkBoard has been used for computationally demanding applications such as the implementation of an autonomous indoor vision-based navigation system with all computations performed onboard (e.g. [116]). The autopilot has been deployed on multiple MAVs. In Paper V, we describe examples of MAV systems built with the LinkBoard and their applications and an in-flight experimental performance evaluation of a newly developed attitude estimation filter.

Chapter

3 Ad-hoc Wireless Communication Networks

3.1 Preliminaries

Recent studies have shown that the severity and frequency of natural disasters, such as wildfires, hurricanes, earthquakes, and floods, are increasing [3, 57]. These events have a significant economic impact and, most importantly, typically lead to many human casualties. Therefore, governments, in collaboration with national and international organizations, work on diverse programs and policies that aim at disaster prevention and cutting-edge emergency response (e.g. [25]). As a result, a significant effort has been put into supporting emergency rescue teams with autonomous intelligent systems to increase rescue operations' efficacy and responders' safety, as rescue operations typically occur in hazardous conditions [38, 100, 110]. Robotic systems can be rapidly deployed to collect sensory data (i.e. images and video streams) in areas that are dangerous or inaccessible to rescue operators. Supplied information can provide an up-to-date overview of the situation and contribute significantly to planning efficient and safe rescue missions. However, using robotics platforms in emergency rescue applications extends beyond these passive information-gathering scenarios.

One of the significant issues rescue teams face during the initial phases of their operations is the need for reliable means of communication [102, 127, 130]. The lack of predictable and resilient communication infrastructure hinders the efficiency of rescue operations as the planning and coordination of activities is difficult. Additionally, it poses safety threats since the whereabouts of team members and discovered hazards cannot be reliably communicated. In the aftermath of a disaster, rescue teams must rely on something other than existing telecommunication systems, as these are typically nonfunctional. Therefore, the work presented in this chapter focuses on developing base functionalities required for UAV-based rapid deployment of ad-hoc communication networks in the initial phases of rescue operations.

Utilizing teams of UAVs for the deployment of ad-hoc communication infrastructures has been an active research topic over the past two decades [143]. The typical approach proposed in the literature is to use multiple UAVs equipped with transceivers to establish an ad-hoc network that can serve as a communication infrastructure not only among UAVs but also between any network clients (e.g. emergency responders) located on the ground and connected to the network. In such a setup, the UAVs serve as relays or communication nodes and are required to stay in the air at designated positions to provide uninterrupted service. This concept was formalized in [13] as Flying Ad-Hoc Networks (FANETs), where the main differences between FANETs and other network families such as Mobile Ad-Hoc Networks (MANETs) and Vehicle Ad-Hoc Networks (VANETs) are discussed together with challenges related to their deployment. Examples of work related to the deployment of FANETs include the UAVNet [99], where authors propose to use small UAVs positioned at low altitudes to create a Wireless Mesh Network (WMN). UAVs are equipped with wireless transceivers based on the IEEE 802.11g standard and act as relays. Work presented in [40] focuses on using the concept of swarm behavior to deploy self-organized aerial mesh networks. Proposed algorithms include a swarm mobility algorithm used to calculate UAV positions and a distributed charging scheduler that deals with the problem of continuous operation (i.e. when a particular UAV is allowed to recharge its battery to maintain overall network connectivity). In [39] a solution based on mobile Long Term Evolution (LTE) technology is presented. In this case, the authors propose to use a fleet of UAVs equipped with LTE femtocell base stations to offer additional network resources if the existing fixed wireless infrastructure is saturated in disaster scenarios. A support software tool is presented that calculates the required number of UAVs and their optimal locations that maximize the communication network user coverage. The calculation considers the specifications of the base stations and the power requirements. In [27] a method for optimal placement of UAVs used as relays is presented. The algorithm maximizes the end-to-end signal-to-noise ratio using various channel models and common relaying protocols. A performance comparison between different network configurations (multi-hop single link vs. multiple dual-hop links) is presented.

Solutions based on FANETs have several advantages but also pose additional challenges. For example, network configurations can be easily adjusted or repaired due to the high mobility of UAV platforms. On the other hand, the UAVs' endurance may be a limiting factor in ensuring uninterrupted network services. Furthermore, UAVs need to refuel or recharge batteries, and the problem of continuous operation needs to be addressed (e.g. by using scheduling algorithms [40, 126]).

Contrary to the deployment of FANETs, the approach considered in this thesis focuses on UAV-based rapid deployment of *terrestrial* ad-hoc network infrastructures. In this case, a fleet of UAVs is tasked to deliver a set of communication nodes that would serve as the physical communication infrastructure for a specific region via air delivery.

3.2 Wireless Mesh Networks

Wireless Mesh Networks (WMNs) are an emerging technology well-suited for applications requiring the prompt deployment of ad-hoc network infrastructures. Generally, WMNs are cost-efficient, resilient, and easy to maintain compared to other technologies, such as satellite communication links.

The hybrid WMN architecture proposed in this thesis consists of two types of communication devices: the Router Nodes (RNs) and the Gateway Nodes (GNs). The RNs are organized in a mesh topology using wireless links and act as the *backbone* of a network. They serve as access points and relay traffic between clients connected to the network. The RNs considered in this thesis are commercial off-the-shelf routers compliant with the IEEE 802.11a/n technical standards. Generally, the performance of *backbone* WMNs degrades quickly as the number of nodes in the network increases. As a result, such networks deployed over large geographical areas offer restricted throughput and overall capacity. This limitation is independent of the number of frequency channels the network devices use [59, 68, 78, 83]. In order to address the scaling problem of large WMNs, some RNs can be assigned to act as gateways to other networks.

In most typical applications, the GNs provide Internet access through wired connections, and the resulting architecture combines multi-hop wireless mesh networks with traditional wired local area networks (LANs). GNs act as sinks in the network where most of the data traffic is transmitted from RNs to GNs, thus effectively increasing the network's overall capacity and throughput. However, using wired LAN infrastructure in emergency response applications may be challenging as deploying such infrastructure rapidly during time-critical operations may be physically impossible. Therefore, in Paper VII, we propose a hybrid WMN topology that combines the RNs and specialized GNs capable of using long-range wireless radio links for GN-GN communication. The architecture design has been inspired by previous work [41, 125], and its overview is depicted in Figure 3.1. The GNs act as bridges between distant nodes in multi-hop mesh networks, reducing the traffic relayed by RNs, and consequently increasing the overall network performance. Further, the GNs can provide client connectivity to the Command and Control Centers (C2) and the Internet.

Generally, when designing networks that greatly rely on wireless technologies, one has to consider the potential for radio wave interference which may degrade the network's performance. Consequently, the proposed hybrid WMN infrastructure is assumed to use GNs that operate on different radio frequencies than the basic RNs to minimize the potential of interference with RN-RN links. GNs compliant with the IEEE 802.16 WiMAX standard or mobile LTE/5G cellular stations[1] are two examples of commercially available technologies that can be used for this purpose. However, due to their characteristics, such as physical size, and high power requirements for long-range radio links, gateway nodes are more expensive than RNs, and their num-

[1] e.g. www.combitech.se/tjanster/kommunikation/private-networks-lte/

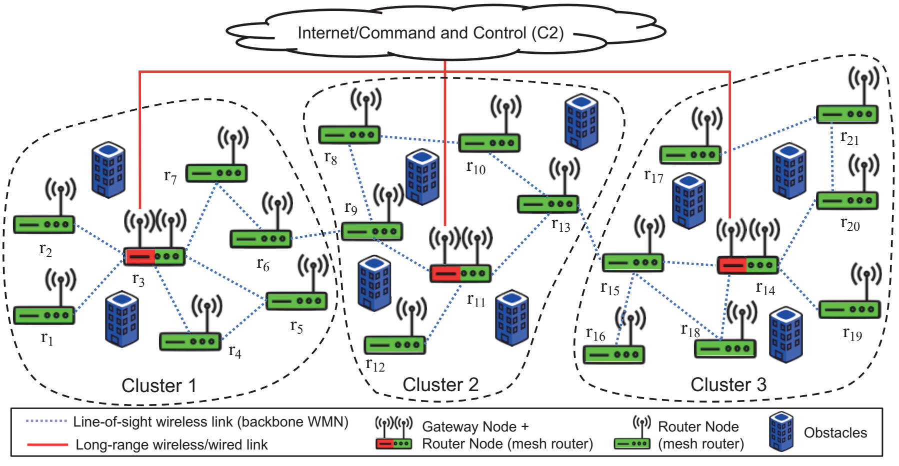


Figure 3.1: Overview of the proposed hybrid Wireless Mesh Network topology.

ber should be minimized. Further, the GNs may require manual deployment and installation, unlike their battery-powered, smaller counterparts, router nodes, that can be autonomously deployed using UAVs.

A proof of concept design of a UAV deliverable RN communication node has been developed and is presented in Paper VI. The node design features an efficient deployment technology based on autonomous release mechanisms and airdrop by a parachute.

Designing an effective and resilient hybrid WMN network architecture is a complex endeavor with several factors to consider. The most crucial are two key issues. The first relates to determining the optimal RN placement (RNP) that maximizes overall network coverage while preserving connectivity. The second is finding a minimal number of gateway node placements (GNP) that ensure an adequate level of Quality of Service (QoS) based on criteria such as maximum communication delay, relay load for each RN, and gateway node capacity limits.

3.3 Router Node Placement

The RNP problem tries to determine how to optimally place routers in a WMN backbone network (i.e. a mesh network consisting of only router nodes). Most common mathematical models considering the RNP problem [86, 142] aim at maximizing two network performance measures: *network connectivity* and *client coverage*. The network connectivity measures the degree of connectivity between router nodes, and client coverage measures the number of client nodes connected to the WMN. Finding router node placement in a specific geographical area for a WMN that optimizes both performance measures has been the focus of several recent research publications [87, 88, 89], although not in the context of UAV deployment or our target application scenarios.

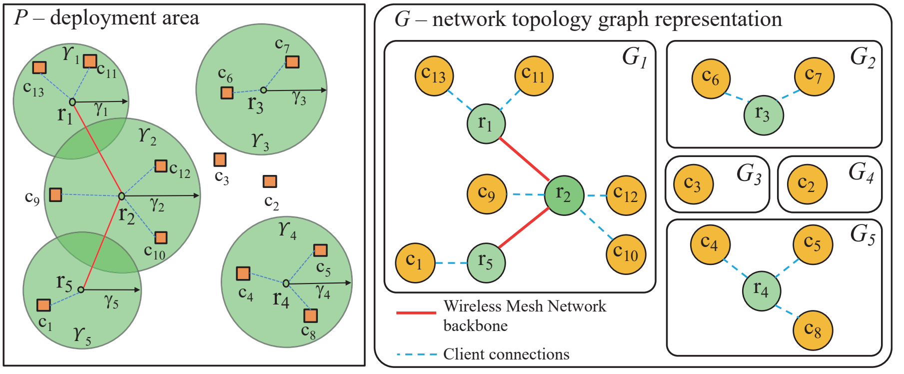


Figure 3.2: Wireless Mesh Network example. Overview of the backbone WMN deployed in an area P (left). Topology graph representation of the WMN (right).

Let us start by formally specifying a *standard* RNP mathematical model found in the literature [86, 142], which is defined as a continuous optimization problem. A WMN comprises a set of mesh router nodes (RNs) and mesh clients. RNs serve as access points for mesh clients (rescuers or victims in our domain) and are interconnected with point-to-point wireless links creating a backbone for the network. Figure 3.2 shows an example of a WMN consisting of five mesh routers r_i and 13 mesh clients c_j deployed in the area P.

A network topology graph, $G = (V, E)$, can be constructed and used for analysis given a WMN topology (e.g. Figure 3.2 (right)). A graph's vertices (V) comprise mesh clients and routers. The edges (E) represent connectivity. An edge between two routers is added when the routers are in the communication range. A client/router edge is added when the client is in the communication range of the router.

Formally, a WMN for the RNP problem, is defined as a set of interconnected devices in a universe $U = R \cup C$, where $R = \{r_1, \ldots, r_n\}$ is a set of *n* mesh router nodes and $C = \{c_1, \ldots, c_m\}$ is a set of *m* mesh clients. Each r_i represents the ith mesh router and consists of a tuple $\langle r_i^X, \gamma_i, \Upsilon_i \rangle$ where $r_i^X = (x_i, y_i) \in \mathbb{R}^2$, is the position of the router node, γ_i is its nominal communication range, and Υ_i is the circle representing its radio coverage centered at the r_i^X position with radius γ_i for $i \in \{1, \ldots, n\}$. Each c_j corresponds to the jth client where $c_j^X = (x_j, y_j) \in \mathbb{R}^2$, is the position of the client node for $j \in \{1, \ldots, m\}$ in the deployment area.

Consequently, the network topology graph $G = (U, E)$ will consist of vertices from R and C, with a graph edge connectivity constraint on members of E defined as:

$$\begin{aligned} e(r_i, r_j) \in E(G) &\iff \Upsilon_i \cap \Upsilon_j \neq \varnothing & i, j \in \{1, \ldots, n\} \\ e(c_j, r_i) \in E(G) &\iff c_j^X \in \Upsilon_i & i \in \{1, \ldots, n\}; j \in \{1, \ldots, m\} \end{aligned} \tag{3.1}$$

Note, that a network topology graph G for a particular set of RNs and client positions may not be connected. This means it may consist of several subgraphs as in the example WMN shown in Figure 3.2, where the graph G comprises five subgraphs (i.e. G_1, ..., G_5). In the general case, the size of the greatest subgraph component in $G = G^1 \cup G^2 \cup \ldots G^h$ represents the *network connectivity* measure which is defined as:

$$\phi(G) = \max_{i \in \{1,\ldots,h\}} \{|G^i|\} \tag{3.2}$$

Subsequently, for a given network topology graph G, the number of clients connected to the network representing the *client coverage* measure is defined as:

$$\psi(G) = |\{j; d(c_j) > 0 \quad \text{for} \quad j \in \{1,\ldots,m\}\}| \tag{3.3}$$

where $d(c_j)$ is the degree of vertex c_j in the network topology graph G.

Based on the definitions introduced so far, the *standard* RNP problem can be specified as the following optimization problem. Given a target deployment set P (i.e. deployment area), and a set of m clients C, find n mesh router positions r_i^X for $i \in \{1,\ldots,n\}$, that maximize a bi-objective cost function consisting of the normalized values of the *network connectivity* ($\frac{\phi(G)}{n+m}$) and the *client coverage* ($\frac{\psi(G)}{m}$).

The *standard* RNP problem belongs to the class of NP-hard problems. Consequently, no algorithms exist that can provide optimal solutions in polynomial time. Instead, the main focus of the recent research was on developing efficient heuristic or meta-heuristic methods, such as evolutionary algorithms. The standard approach to dealing with the bi-objective nature of the cost function is to either apply hierarchical (e.g. [142]) or simultaneous (e.g. [86]) optimization procedures.

Solutions to the *standard* RNP problem have limited practical use as the problem formulation does not account for two crucial factors important in real-world WMN network deployments, especially in emergency rescue application scenarios. First, in the *standard* RNP problem, the client positions are assumed to be known beforehand. For some environments, typical client positions could be presumed or estimated (e.g. based on urban structure). Such estimations, however, cannot be done in rescue scenarios as the typical post-disaster environments are unstructured, the network clients (rescuers or victims) are highly mobile, and the rescue teams usually perform an exhaustive search of the disaster area in question. Another factor to consider is related to *network connectivity* and the resiliency of the network connections. The mesh router's signal strength in any given point depends on the distance to another router and on any physical structures, such as obstacles in the space between them. Consequently, to fully utilize the range of a mesh router and maximize the robustness of links between routers, environment models must be considered when calculating the WMN configuration.

For these reasons, in Paper VII, we propose an *extended* RNP problem formulation that includes additional constraints and introduces an alternative *network coverage* measure as the optimization cost function. Additional constraints include enforcing a line-of-sight requirement between interconnected mesh routers and excluding obstacle areas from potential node placements. The latter constraint relates to the example mission scenario depicted in Figure 1.2, where one wants to avoid delivery of router nodes on collapsed building structures or densely vegetated areas

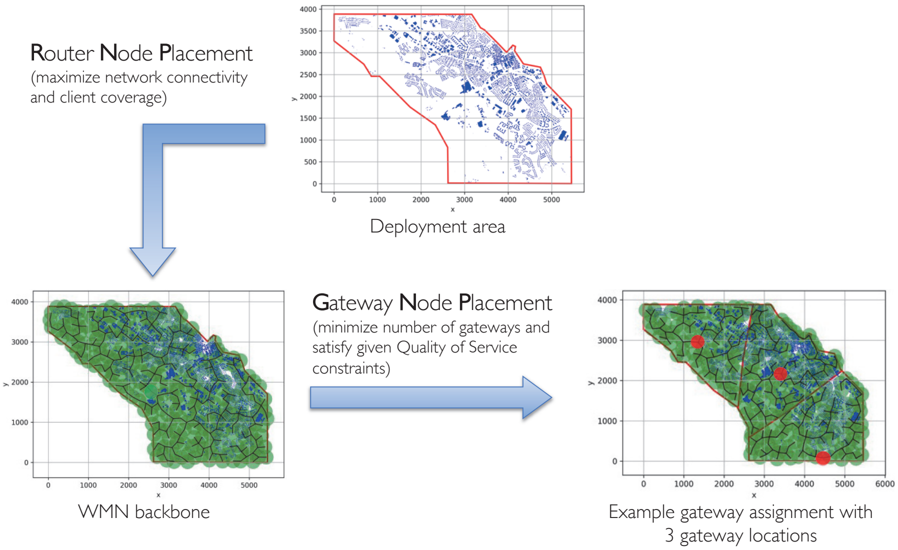


Figure 3.3: Overview of the router and gateway placement problems.

to increase the robustness of the RN-RN connections. Furthermore, the alternative *network coverage* measure is expressed as the total geographical area covered by the WMN, effectively removing the need to specify the client positions beforehand (i.e. the client set $C = \varnothing$). While the proposed *extended* RNP problem is generally more complex, its solutions are considerably more relevant for real-world scenarios.

One major contribution presented in Paper VII is a novel heuristic algorithm called the RRT-WMN, developed to solve the *extended* RNP problems efficiently. The algorithm is an extension of the Rapidly Exploring Random Trees (RRT) [77] algorithm used in motion planning (Section 2.1). Unlike the standard RRT, the RRT-WMN searches for the best possible graph configuration using a heuristic that maximizes RNP objectives.

3.4 Gateway Node Placement

The gateway node placement problem (Figure 3.3) focuses on selecting a minimum number of gateway locations in the WMN backbone network so that the QoS constraints reflecting the network's performance are guaranteed. The most common formulation found in the literature [8, 12, 46] defines the problem as an Integer Linear Program (ILP). The full formal definition is provided in Paper VII. The model assumes a graph representing the WMN backbone network is given (i.e. the router node placements).

Finding a solution to the GNP problem is done by dividing the entire backbone network into disjoint clusters (i.e. sub-networks). Within each cluster, a single gateway is appointed to serve all RNs assigned to that particular cluster. Gateway locations are chosen to maximize the network's performance by considering QoS constraints. The constraints typically regard measures of network delay, throughput, and capacity. Consequently, the overall goal is to find a minimum number of gateway locations while satisfying given QoS constraints. An example GNP solution with three sub-networks and gateway assignments is depicted in Figure 3.3.

The most common QoS constraints proposed in the literature (e.g. [8, 12, 46]) and considered in this thesis include the following:

- maximum communication delay R_{QoS}. The constraint is defined as the maximum number of hops the information has to travel between a router node and the gateway to which the RN is assigned, as each re-transmission increases the total delay. Effectively, the R_{QoS} is an upper bound on the cluster radius.
- maximum relay load for each router node L_{QoS}. The constraint ensures an adequate throughput within each cluster is guaranteed, as information sent to the particular gateway may need to be relayed by intermediate RNs. Hence, the L_{QoS} is an upper bound on the number of router nodes that rely on re-transmission in shortest paths that lead to a gateway from all RNs.
- gateway throughput S_{QoS}. The constraint considers the bandwidth capacity of gateway nodes since a gateway potentially has to cope with traffic from all RNs within each cluster. The S_{QoS} is defined as an upper bound on the cluster size.

In the context of the application domain considered in this thesis, where the goal is to deploy an ad-hoc communication network in emergency rescue operations rapidly, efficient solutions to the combined RNP-GNP problem are required. Ideally, a uniform formal model that combines RNP and GNP problems would be preferred. Unfortunately, as in the case of the RNP, the GNP problem is in the class of NP-hard problems [46]. Due to the complexity of both of these problems individually, they are most often considered separately. This is except for work presented in [81, 120] where the ILP model includes a selection of placements for the router nodes. However, solving such a problem requires extensive computational time, and the router node placement considered is limited to a set of predefined locations.

The approach adopted in this thesis considers the combined RNP-GNP problem as a composition of RNP and GNP problems defined by their respective formal models. In Paper VII, we propose two alternative algorithms for solving the combined RNP-GNP problem. The first approach applies a simple strategy of sequentially solving the RNP and GNP problems. First, the initial RNP problem is solved using the proposed RRT-WMN algorithm, ensuring the WMN network topology graph is fully connected while maximizing its geographical coverage. Then, the resulting backbone WMN network is used as input to the graph clustering technique, which assigns minimal gateway locations that satisfy the given QoS constraints. Graph clustering methods for GNP problems have been an active research topic with many algorithms proposed. In this work, we adopted a well-established method developed by Aoun et al. [8], the Weighted Recursive Dominating Set.

The second technique proposed, *WMNbyAreaDecomposition*, applies a more deliberate method to solving the RNP-GNP problems. Intuitively, the algorithm applies a divide-and-conquer strategy to decompose the combined problem into single RNP problems that can be solved efficiently and concurrently using the RRT-WMN algorithm. In short, the algorithm starts by dividing the target geographical area into disjoint sub-regions, where simpler RNP problems are defined and solved. The algorithm then calculates the optimal gateway locations in each sub-region. Finally, the resulting hybrid network configuration is evaluated. The procedure is applied recursively, increasing the number of sub-regions until the given QoS constraints are satisfied. Effectively, the *WMNbyAreaDecomposition* generates solutions that simultaneously consider constraints and optimization objectives associated with the RNP and GNP problems. Diving the deployment area into a set of disjoint sub-regions relies on solving the *area partitioning problem* [61], discussed in the next section.

3.5 Area Partitioning

Polygon partitioning is an important class of problems in the field of computational geometry, which has been extensively studied for decades [108]. The problem has many variations with vast applications, for example, Very Large Scale Integration (VLSI) circuit design [10][9], pattern recognition [52], image processing [98], database systems [93], or parallel computing [29], to name a few. In general terms, these problems deal with partitioning a polygon into a set of non-overlapping primitive shapes whose union is equivalent to the original polygon. Depending on the application domain, various formal problem definitions have been proposed, where polygons are decomposed into sets of triangles [11, 19, 37], rectangles [82], trapezoids [10, 9], and sub-polygons [1, 29, 26, 62, 74, 85, 104] with or without additional size, perimeter, or other constraints.

The *area partitioning problem* was first introduced by Hert et al. [61] in the context of terrain covering applications in robotics. These application scenarios require algorithms that can divide an area into sub-regions that can be assigned to individual robots for tasks such as exploration, surveillance, or data collection.

Formally, the *area partitioning problem* can be described as follows. Given a simple[2] polygon $\mathcal{P}$, decompose the polygon into n disjoint sub-polygons $\mathcal{P}_1$ to $\mathcal{P}_n$. The area of each sub-polygon ($\mathcal{A}(\mathcal{P}_i) : i \in I_n \in \{1, \ldots, n\}$) is specified by a weight ($\omega_i \in \Omega$). Weights define area sizes as a proportion of the total area of the polygon $\mathcal{A}(\mathcal{P})$. Thus, the area partitioning problem is defined as follows:

[2]a polygon with no self-intersection

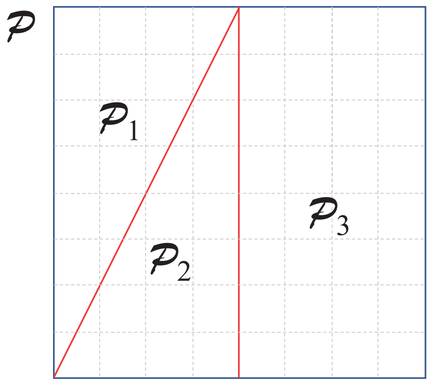


Figure 3.4: An example area partitioning problem and its solution.

$$\mathcal{P} = \bigcup_i \mathcal{P}_i \tag{3.4}$$

$$\mathcal{P}_i \cap \mathcal{P}_j = \varnothing \qquad \forall i \neq j \tag{3.5}$$

$$\mathcal{A}(\mathcal{P}_i) = \omega_i \cdot \mathcal{A}(\mathcal{P}) \qquad \forall i \tag{3.6}$$

$$\sum_i \omega_i = 1 \tag{3.7}$$

Figure 3.4 shows an example area partitioning problem and a solution where the polygon $\mathcal{P}$ is divided into three sub-polygons $\mathcal{P}_1, \mathcal{P}_2, \mathcal{P}_3$ with 25%, 25%, and 50% area size in proportion to polygon $\mathcal{P}$, respectively.

A polynomial-time algorithm for solving the area partitioning problem has been proposed by Hert et al. [61]. The algorithm utilizes a divide-and-conquer strategy combined with a sweep-line approach to generate sub-polygons guaranteed to satisfy the exact area size constraints.

While the main focus of the area partitioning problem defined in Eq. 3.4-Eq. 3.7 is to satisfy the area size constraints, other essential factors are not considered. These factors include the shape characteristics of the generated sub-regions, which can substantially affect the quality of solutions provided for the target applications. *Compactness* or *fatness* of a polygon is one of the metrics that can be used to differentiate the shape properties of sub-regions.

Several compactness measures have been proposed in the literature, most notably with applications in Geographic Information Science (GIS) [84]. An example application is redistricting, which deals with establishing electoral district boundaries for political elections to avoid gerrymandering [107, 112, 118]. Generally, compactness measures are unitless scores calculated by comparing the geometric properties of a given polygon (e.g. area, perimeter) to the properties of a parametrized base geometric shape (e.g. circle). Examples of two compactness scores, the Polsby-Popper [107] and Schwartzberg [118] score for different shapes with equal area

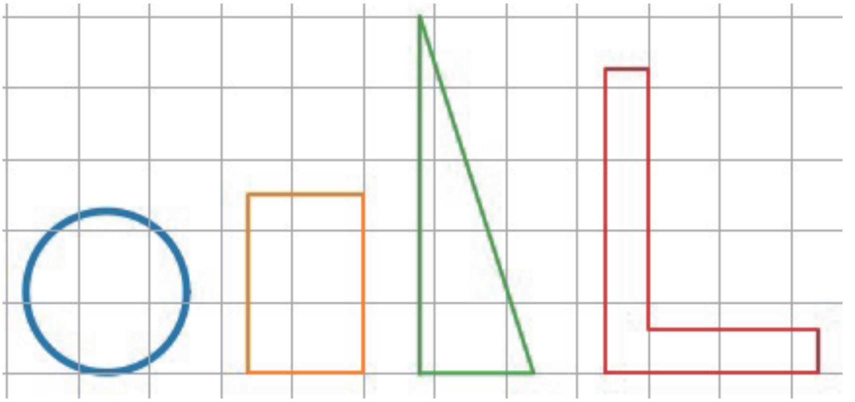


Figure 3.5: Examples of compactness scores for different shapes with equal areas.

sizes, are presented in Figure 3.5. Both scores use a circle as the base shape since it is considered the most compact. Consequently, both scores for a circle are equal to 1.0, and as the shape compactness degrades, the scores' values decrease.

It has been shown that in the terrain covering applications, the compact sub-regions are preferred. This stems from the fact that the plans generated within compact sub-regions are generally more efficient, increasing the overall efficiency with which the task is solved (e.g. [21, 123]). Similarly, generating compact sub-regions turned out to be essential in the *WMNbyAreaDecomposition* algorithm proposed in Paper VII for solving the combined RNP-GNP problems. In this case, sub-regions generated in the divide-and-conquer step of the algorithm resulted in more optimal sub-network topology graphs generated, which required fewer router and gateway nodes in the final solutions.

For these reasons, in Paper VIII we have focused on the *area partitioning problem* with additional shape constraints. We propose an extended area partitioning problem formulation where the goal is to divide a polygon into a set of disjoint connected sub-polygons while maximizing the sub-polygons' compactness [118] and satisfying the area size constraints. The problem formulation is based on a grid cell discretization and a potential field model [76]. We propose an efficient algorithm for solving the new area partitioning problem. The algorithm includes several optimization techniques combined with two post-processing methods. We present an empirical evaluation of the proposed algorithm on a set of randomly generated non-convex polygons and comparison with the existing state-of-the-art technique [61]. Finally, we provide two example applications of the algorithm that include the terrain covering using UAVs and GIS-related problem of redistricting.

CHAPTER

4 Summary and Discussion

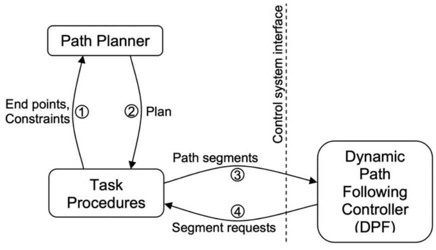
This thesis has focused on two problems related to use and deployment of UAVs in real-world emergency response application scenarios. As such the thesis has been divided into two parts. In part I we considered the problems associated with increasing of autonomy of UAVs by considering the problem of safe navigation in dynamic and changing environments. Part II has focused on services which UAVs can provide in disaster relief scenarios. In particular, we have focused on functionalities required for UAV-based deployment of ad-hoc communication networks which could be used in the first phases of a rescue operation.

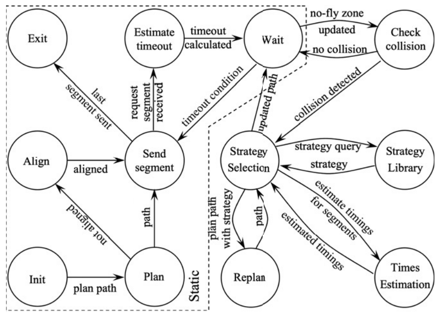
In this chapter, we summarize the included publications, discuss the results in the context of the research questions and provide a short discussion on possible future work.

4.1 Summary of Original Work

Paper I Mariusz Wzorek and Patrick Doherty. "Reconfigurable Path Planning for an Autonomous Unmanned Aerial Vehicle." In: *Proceedings of the International Conference on Hybrid Information Technology.* Vol. 2. IEEE. 2006, pp. 242–249.

In this paper, we propose a motion planning framework that integrates two sample-based motion planning techniques, Probabilistic Roadmaps [73] and Rapidly Exploring Random Tree [77], with the low-level control mode of the UAV. The framework allows for the dynamic reconfiguration of motion plans when currently executed plans are invalidated due to changes perceived in the environment. In short, the segmented paths generated by planners are executed by feeding the low-level control mode with one segment at a time. The execution of the entire path is monitored for potential contingencies that





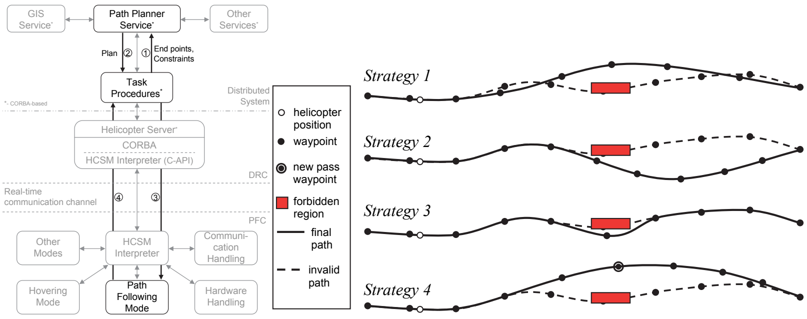
may invalidate parts of the plan. We define several *replanning strategies* that the framework can apply to repair invalid plans. Each strategy progressively re-uses more of the initially generated plan, thus reducing planning times but potentially producing less optimal plans. The framework estimates the time window available for applying a plan repair strategy. A simple heuristic is used to choose the best possible repair option that guarantees a collision-free path is executed at all times, given the available time window. Empirical results show that sample-based motion planning techniques used with such a framework offer a surprisingly efficient method for dynamically reconfiguring motion plans to react to contingencies that can occur during the execution of a plan. The presented framework has been implemented, integrated, and verified with hardware-in-the-loop simulations using the Yamaha RMAX UAV system.

Individual contributions: The author of this thesis conceived the original ideas described in the paper. In addition, the author wrote the framework's software implementation, performed the presented experimental evaluations, and took the lead in writing the manuscript.

Paper II Mariusz Wzorek, Gianpaolo Conte, Piotr Rudol, Torsten Merz, Simone Duranti, and Patrick Doherty. "From Motion Planning to Control – A Navigation Framework for an Unmanned Aerial Vehicle." In: *Proceedings of the 21st Bristol International Conference on UAV Systems.* 2006, pp. 1–8.

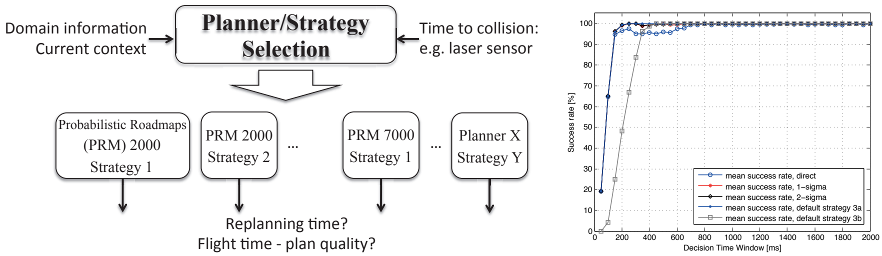
In this paper, the framework proposed in Paper I is described in the context of a hybrid deliberative/reactive software architecture developed for the Yamaha RMAX UAV platforms [45]. The paper focuses on the navigation subsystem of the architecture. A detailed description of the dynamic path following control mode [31] and its use within the motion planning framework proposed in Paper I is discussed. Examples of real-world mission executions where the UAV dynamically replans a path to avoid added no-fly zones are presented.

Individual contributions: The author of this thesis conceived the ideas related to the motion planning framework described in the paper. Furthermore, the



author actively participated in the presented experimental evaluations and took the lead in writing the manuscript.

Paper III Mariusz Wzorek, Jonas Kvarnström, and Patrick Doherty. "Choosing Path Replanning Strategies for Unmanned Aircraft Systems." In: *Proceedings of the International Conference on Automated Planning and Scheduling.* Vol. 20. 1. 2010, pp. 193–200.



The framework presented in Papers I-II used a simple user-defined heuristic for selecting an adequate plan repair strategy based on the time window available. This paper extends the framework with a more elaborate selection mechanism that utilizes machine learning techniques.

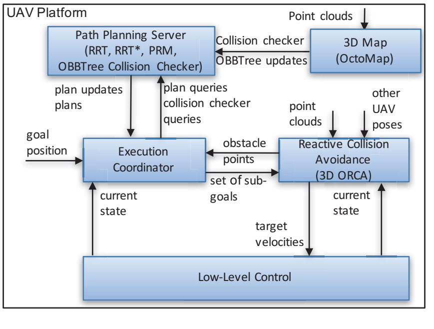
In Papers I-II, we defined several replanning strategies to determine which parts of the original path are replaced and which are reused. The choice of a strategy has been shown to significantly affect the quality of the repaired plan and the time required for replanning. In this paper, we extend the set of replanning strategies the framework can apply by considering the motion planning techniques' parametrization. For example, PRM planners use a roadmap graph generated in an offline phase to solve planning problems. The number of nodes in the graph is one of the planner input parameters. Generally, by increasing the number of nodes in the graph, the plan quality will increase. The graph density, however, will also impact the computation time required for generating plans.

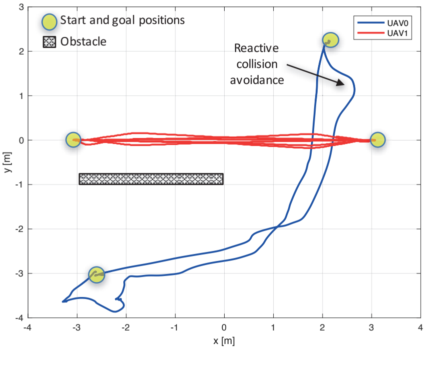
One of the objectives of the presented framework is always to choose a re-planning strategy that will yield the highest quality possible within the available time. However, while there may be a general trend for one strategy to be better or faster, the exact time requirements for most strategies will vary considerably depending on factors such as the characteristics of the environment around the original path and the remaining distance to the destination. Thus, to solve the strategy selection problem, we have two alternatives. First is always to choose a simple strategy for which we can find a low upper bound on the computation time requirements. The second alternative is to generate better and more informed predictions by *learning* how the characteristics of the environment affect timing and quality.

In this paper, we select the second alternative, where we investigate the use of machine learning (specifically, support vector machines) to choose the repair strategy and the planning parameters that yield the highest expected plan quality given the time available for replanning. First, a set of prediction models is built offline for each map using the hardware-in-the-loop simulations. Then, the models are used during the navigation to predict the time requirements for each repair strategy and the expected plan quality. These predictions are used to select the best strategy given the time available. Experimental results show that this approach is superior to a simple strategy selection resulting in flight times improved by up to 25% while maintaining high success rates.

Individual contributions: The author of this thesis conceived the original ideas described in the paper. In addition, the author wrote the necessary software implementation, performed presented experimental evaluations, and took the lead in writing the manuscript.

Paper IV Mariusz Wzorek, Cyrille Berger, and Patrick Doherty. “A Framework for Safe Navigation of Unmanned Aerial Vehicles in Unknown Environments.” In: *Proceedings of the 25th International Conference on Systems Engineering*. IEEE. 2017, pp. 11–20.

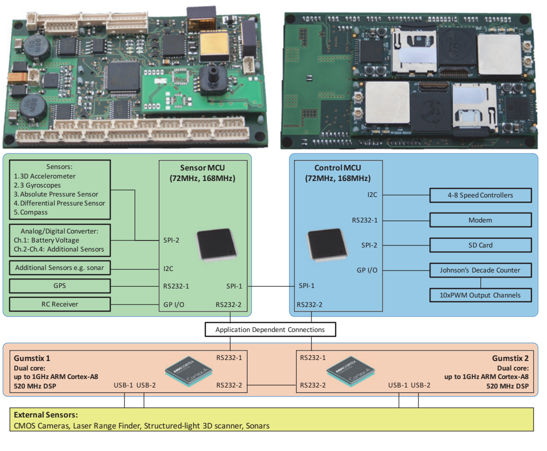




In Paper IV, we focus on solving the problem of safe navigation, where multiple UAVs operate in unknown environments. We propose a framework that combines sample-based path planning techniques with a reactive collision avoidance control approach and 3D map building. The system leverages the advantages of integrating a fast sense-and-avoid type control, which guarantees real-time execution, with computationally intensive path planning algorithms that generate globally optimal plans. Several sample-based path planning algorithms based on Probabilistic Roadmaps and Rapidly-Exploring Random Tree and its variations [72, 71] have been integrated. The Optimal Reciprocal Collision Avoidance (ORCA) technique [14] is the basis for the reactive sense-and-avoid controller used for path execution. Additionally, the framework includes functionalities for 3D map building where an octree-based map structure, the OctoMap [64], is used to represent the perceived environment. The path planning algorithms rely on fast and efficient collision checks, therefore, a method for incremental updates of the collision checker data structures is proposed. The framework has been implemented and deployed on a small-scale quadrotor platform. The UAV used in the experiments was equipped with a structured-light depth sensor to obtain information about the environment in the form of an occupancy grid map. The system has been tested in a number of simulated missions as well as in real flights, and the results of the evaluations are presented in the paper.

Individual contributions: The author of this thesis conceived the original ideas described in the paper. In addition, the author wrote the necessary software implementation, performed presented experimental evaluations, and took the lead in writing the manuscript.

Paper V Mariusz Wzorek, Piotr Rudol, Gianpaolo Conte, and Patrick Doherty. "LinkBoard: Advanced Flight Control System for Micro Unmanned Aerial Vehicles." In: *Proceedings of the International Conference on Control and Robotics Engineering.* IEEE. 2017, pp. 102–108.



In this publication, we present the design and development of the LinkBoard, an advanced flight control system for micro UAVs. We describe the hardware and software aspects of the LinkBoard design in detail. The hardware development aimed to minimize the autopilot's physical size and weight while maximizing the available computational power. The LinkBoard includes four processing units and a complete inertial measurement unit required for implementing autonomous navigation capabilities. The micro-controller units (MCUs) used in the design are based on the STM32[1] chip family, which makes it easy to upgrade when new and faster MCUs become available. The LinkBoard weighs 30g in full configuration and is smaller than the size of a credit card. Software developed onboard is modular, where configurations of the functional components are stored in the integrated solid-state memory. Such a design is very flexible as it allows for complete reconfiguration of the system behavior without the need for recompiling and uploading the firmware. An example system configuration for a quadrotor platform demonstrating the versatility of the software design is presented in [114], where different high-level flight behaviors are achieved through the parametrization of flight commands implemented onboard the LinkBoard.

Due to the available onboard computational power, the LinkBoard has been used for computationally demanding applications such as the implementation of an autonomous indoor vision-based navigation system with all computations performed onboard (e.g. [116]). The autopilot has been manufactured and deployed on multiple UAVs. In the paper, we describe examples of UAV systems built with the LinkBoard and their applications and an in-flight experimental performance evaluation of a newly developed attitude estimation filter. The LinkBoad has been used in experimentation presented in Paper V.

Individual contributions: The author of this thesis conceived the idea of the autopilot development described in the paper. In addition, the author led the hardware design and prototyping processes and contributed equally to the software architecture design and its implementation. The author also took the lead in writing the manuscript.

Paper VI Mariusz Wzorek, Cyrille Berger, Piotr Rudol, and Patrick Doherty. "Deployment of Ad Hoc Network Nodes Using UAVs for Search and Rescue Missions." In: *Proceedings of the International Electrical Engineering Congress.* IEEE. 2018, pp. 1–4.

In Paper VI, we focus on the design and development of physical devices that can be used for rapid UAV-based deployment of ad-hoc wireless networks in emergency response missions. The development has been driven by a mission scenario where a fleet of UAVs is used to deliver a set of communication nodes

[1]https://www.st.com/en/microcontrollers-microprocessors/stm32-32-bit-arm-cortex-mcus.html

that would serve as the physical communication infrastructure for a specific region.

The paper presents a proof of concept design of a UAV deliverable communication node called CommKit. The CommKit integrates several hardware components enclosed in a small box, including a mesh router, LiPo battery, Raspberry Pi computer board, GPS/IMU sensor, digital servo, and a parachute system. The mesh router is the central part of the CommKit as it is used to create an ad-hoc wireless network between multiple CommKits. The release and attachment of a CommKit to a UAV fuselage is realized using the digital servo mounted outside of the box shell. The integrated parachute system ensures safe in-air delivery of the node.

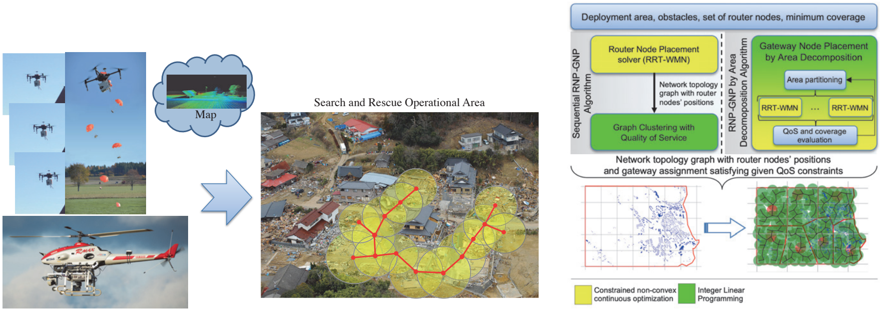
The Raspberry Pi computer board hosts the deployment algorithm, which implements functionalities required for safe in-air delivery. In addition, the GPS/IMU sensors integrated with the CommKit allow for implementing certain decision-making and monitoring algorithms important in the applications we are dealing with. For example, deciding when the parachute should be released, monitoring the success of the drop and delivery, reconfiguring the mesh router, or getting the location of each CommKit node after deployment, which can be used for network optimization, repair, or extension.

The deployment algorithm running onboard the CommKit's Raspberry Pi computer is implemented using ROS[2], allowing easy integration with our existing UAV platforms. Two CommKit box prototypes with different mesh router and parachute configurations were tested during four flight-test days, with more than 25 successful delivery missions performed. The experimental evaluation results are presented in the paper.

Individual contributions: The author of this thesis conceived the idea of CommKit node development described in the paper. In addition, the author led the hardware design and prototyping processes. The author also took the lead in writing the manuscript.

Paper VII Mariusz Wzorek, Cyrille Berger, and Patrick Doherty. "Router and Gateway Node Placement in Wireless Mesh Networks for Emergency Rescue Scenarios." In: *Autonomous Intelligent Systems.* 1.1, 2021, pp. 1–30.

[2]Robot Operating System, `ros.org`



In Paper VII, we propose a hybrid wireless mesh network architecture suited for emergency rescue operations. The network consists of two types of nodes: routers and gateways. We then consider two important problems associated with the practical deployment requirements of such ad-hoc communication networks. Namely, we consider the problem of optimal router node placement (RNP) and gateway node placement (GNP).

The RNP problem deals with calculating the optimal positions of router nodes, maximizing two network performance measures: network connectivity and client coverage. Based on our experience with practical mesh network deployments, we propose an extended RNP problem formulation that includes additional constraints. The extended RNP adds line-of-sight constraints between interconnected mesh router nodes and requires the network to be fully connected. Additionally, we propose maximizing the network's geographical coverage instead of client coverage, which removes the need to know the positions of network clients beforehand.

In the paper, we propose an algorithm called RRT-WMN to solve the extended RNP problems efficiently. The algorithm is an extended version of the Rapidly Exploring Random Tree algorithm (RRT) [77] commonly used in motion planning. Unlike the standard RRT, the RRT-WMN searches for the best possible graph configuration using a heuristic that maximizes RNP objectives.

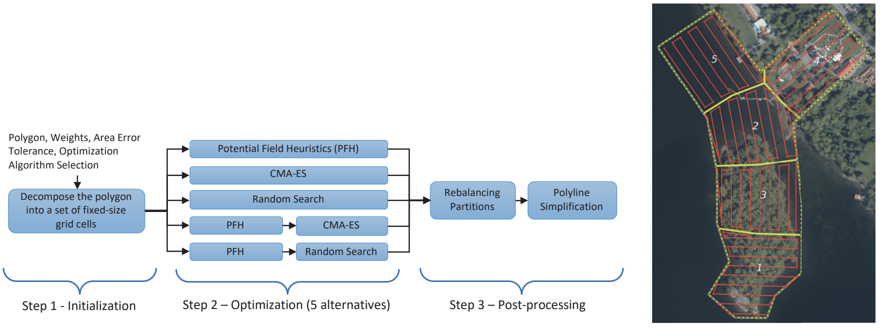
Moreover, in the paper, we consider the combined RNP-GNP problem, which focuses on finding optimal router and gateway node placements while satisfying both extended RNP constraints and Quality of Service (QoS) constraints associated with the network. Two alternative algorithms are presented and evaluated in the paper: the *SequentialRNP-GNP* and *WMNbyAreaDecomposition*. The *SequentialRNP-GNP* combines the RRT-WMN algorithm with a graph clustering technique called Weighted Recursive Dominating Set (WeightedRecursiveDS) [8] by executing them in a sequence. The *WMNbyAreaDecomposition* is a novel algorithm that decomposes the original RNP-GNP problem into a set of simpler RNP problems solved concurrently. First, the algorithm partitions a geographical area into disjoint sub-regions, where for each sub-region, simpler RNP problems are defined and solved efficiently using the RRT-

WMN algorithm. Then, an optimal location of a gateway is calculated within each sub-region, and the network configuration is evaluated. The algorithm continues the decomposition cycle increasing the number of sub-regions until the QoS constraints are satisfied. Effectively, the algorithm finds network configurations with the minimum number of gateways.

The empirical evaluation of the proposed algorithms has been performed using real-GIS models of various sizes and complexities. The results show that the proposed algorithms can solve realistic problem instances efficiently.

Individual contributions: The author of this thesis conceived the original ideas described in the paper. In addition, the author wrote the necessary software implementation, performed presented experimental evaluations, and took the lead in writing the manuscript.

Paper VIII Mariusz Wzorek, Cyrille Berger, and Patrick Doherty. “Polygon Area Decomposition Using a Compactness Metric.” In: *under journal submission.* 2023.



In Paper VIII, we focus on the area partitioning problem, which deals with dividing polygonal areas into a set of disjoint sub-regions with predefined area sizes. Although the problem was first introduced in the context of terrain-covering applications in robotics [61], it has many more application domains, such as urban planning or electoral redistricting. One shortcoming of the original problem formulation is that it considers only area size constraints while neglecting other important aspects, such as shape characteristics of the generated sub-polygons. Compactness is one metric which can be used to measure the shape characteristics of a polygon, and in many application domains, compact sub-regions are preferred. In fact, the work presented in this paper was motivated by the application domain described in Paper VII, where we considered the combined RNP-GNP problem.

In this paper, we propose an extended *area partitioning problem* which considers the compactness of generated sub-polygons in addition to the area size constraints. The extended problem definition uses grid discretization and a potential field model. We propose and evaluate an efficient algorithm for solving the new problem. Generally, by imposing the shape constraints, the algorithm avoids generating sub-regions with sharp corners. This is an essential feature exploited in the router and gateway node placement algorithm presented in Paper VII. Additionally, the new problem and the algorithm have applications to terrain covering in the UAV domain and GIS-related problems dealing with zoning or redistricting.

Individual contributions: The author of this thesis equally contributed to the original ideas described in the paper and took the lead in writing the manuscript.

4.2 Discussion and Future Work

In Chapter 1 we have defined a number of research questions that have been studied and addressed in this thesis. For convenience we repeat those here:

RQ1 How to efficiently integrate motion planning algorithms, control, and perception functionalities within UAV software architectures to solve the problem of autonomous safe navigation in dynamic or changing environments?

- **RQ1.1** How to extend the use of existing motion planning techniques for dynamic or changing environments?
- **RQ1.2** How to integrate motion planning with low-level control and perception?
- **RQ1.3** As the UAVs scale down in size, how can one leverage advances in low-power, small-size electronic components to allow onboard execution of computationally intensive algorithms?

RQ2 How can UAVs be utilized to rapidly deploy ad-hoc communication networks in emergency rescue scenarios?

- **RQ2.1** What are the requirements for designing UAV-deployable communication nodes that can be used to establish an ad-hoc communication network?
- **RQ2.2** What practical constraints should be considered in communication node placement problems?
- **RQ2.3** How can one efficiently solve communication node placement problems?

Research questions RQ1.1 and RQ1.2 were addressed in Papers I-IV. In these publications, we have proposed multiple novel ideas regarding integrating global motion planners with control modes and perception to address the problem of navigation in dynamic or changing environments. As a result, two variants of navigation frameworks have been developed and deployed on real UAV systems. Specifically, we proposed replanning strategies that can be dynamically applied to repair a path during navigation tasks (Papers I-II). We also developed a mechanism for choosing the best strategy (i.e. yielding the highest plan quality) depending on environmental characteristics given the time available for plan repair (Paper III). In the second navigation framework (Paper IV), we have combined motion planners with reactive collision avoidance control mode and map-building functionalities based on point cloud sensor data provided by a depth camera. The reactive control mode applies a sense-and-avoid approach to always guarantee collision-free navigation. At the same time, global motion planners are used to generate updated plans that consider the entire current environment map.

The proposed frameworks have been implemented and evaluated in simulations and real flights to validate the ideas and showcase the system's performance. Although the frameworks have been deployed on UAV platforms, the ideas proposed for integrating the required functionalities can be adapted to other robotic system types, which is an exciting research direction. Additional future work directions include combining ideas from both frameworks and applying the newest advances in machine learning to the problem of replanning strategy selection. It is worth to note that the ideas proposed in Part I of the thesis have been since generalized in some recent work. For example, Choudhury et al. [28] propose a system that dynamically selects among different motion planners included in its *planner ensemble* using machine learning techniques.

Research question RQ1.3 was addressed in Paper V, where we proposed a design of software and hardware architectures for a miniature autopilot specifically designed for MAV platforms. The LinkBoard autopilot has been designed, manufactured, deployed, and evaluated on various MAV systems. The main goal of the design was to minimize physical hardware size maximizing the available computational power of the system. We have integrated the LinkBoard with multiple MAV platforms which use different flight configurations, such as a quadrotor or dual coaxial drive. The LinkBoard enabled the MAV systems to run computationally expensive algorithms onboard, effectively increasing their level of autonomy. Various applications have been shown, for example, an autonomous indoor vision-based navigation system where all computations are performed onboard [116], or implementation of various high-level flight behaviors [114].

In Paper VI, we addressed the research question RQ2.1. In this publication, we have presented a design of communication nodes called CommKits, which include necessary components for the deployment and creation of ad-hoc communication networks. The central part of the CommKit is an 802.11 mesh router used for setting up the communication infrastructure. Other components include several sensors (e.g. GPS, accelerometer) and a delivery mechanism consisting of a digital servo and a parachute system which allows for in-air delivery of the node. The delivery mechanism and the software designed to control it have other uses than in-air delivery. For example, the mechanism has since been adopted to realize the delivery of other payloads (e.g. medical supplies) using UAVs. In that application, the modified CommKit delivery mechanism is mounted on a UAV and integrated with multiple digital servos, allowing multiple packages to be delivered.

Research questions RQ2.2 and RQ2.3 were addressed in Papers VII-VIII, where we have proposed an extended RNP problem and considered combined RNP-GNP problems. The extended RNP problem formulation accounts for additional constraints which are essential in practice when deploying WMN networks. We have proposed and evaluated efficient algorithms for solving both of these problems. Several interesting future work directions have been identified based on this research. First, the presented router and gateway placement algorithms were evaluated using existing GIS world models. In emergency response scenarios, however, it is beneficial to make use of dynamically generated or updated world models, for example, using LiDAR sensors. Such models typically include 3D geometric data, and additional extensions to the algorithms may be considered to ensure the solutions are calculated efficiently. Second, our in-the-field experimentation focused on deployments of barebone WMN networks (i.e. consisting only of router nodes). In future work, it would be valuable to evaluate networks that include router nodes (i.e. CommKits) and gateways, for example, by using the latest 5G private mobile network infrastructures offered by Ericsson[3] or Combitech[4]. Last but not least, the CommKits include several sensors. Therefore, our deployed ad-hoc WMN networks can effectively be viewed as Wireless Sensor Networks (WSNs). WSNs research area in the context of using CommKit nodes remains to be explored.

In conclusion, the research questions formulated in the thesis have been addressed in the included publications. In addition, we have also identified and described several promising future work directions.

[3]https://www.ericsson.com/en/private-networks

[4]www.combitech.se/tjanster/kommunikation/private-networks-lte/

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