UNIVERSITY OF TECHNOLOGY SYDNEY
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Optimal Task Scheduling and Flight Planning for Multi-Task Unmanned Aerial Vehicles

by

Bin Liu

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in Fulfillment of the
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Certificate of Authorship/Originality

I, Bin Liu declare that this thesis, is submitted in fulfilment of the requirements for the award of doctor of philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within the text. This thesis is the result of a Collaborative Doctoral Research Degree program with Nanjing University of Posts and Telecommunications.

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ABSTRACT

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Unmanned aerial vehicles (UAVs), also known as drones, play an important role in various areas due to their agility and versatility. Integrated with many embedded components, the UAV is capable of conducting multiple tasks simultaneously. Coordinating different tasks to a multi-task UAV can be challenging. The reason is that tasks may require different levels of commitment and tolerate different latencies. Another reason is that multi-tasking can give rise to difficulties in the UAV's energy management, as many UAVs are battery-powered. In this thesis, we study the optimal flight planning, control, and routing for the multi-task UAV.

The main contributions of this thesis can be summarized as follows.

- This thesis presents a novel energy-efficient UAV flight planning framework, which integrates UAVs into intelligent transportation systems for energy-efficient, delay-sensitive delivery services. The UAV can dynamically choose actions from cruise speed, full speed, recharging at a roadside charging station, or hitchhiking and recharging on a collaborative vehicle. The objective is to minimize the energy consumption of the UAV and ensure timely delivery. We reveal the conditions under which the UAV's flight planning changes in terms of the remaining flight distance or the elapsed time. Consequently, the optimal flight planning can be instantly made by comparing with the thresholds.
- This thesis presents a new online control framework for multi-task UAVs, which allows a UAV to perform in-situ sensing while delivering goods. A new

finite-horizon Markov decision process (FH-MDP) problem is formulated to ensure timely delivery, minimize the UAV's energy consumption, and maximize its reward for in-situ sensing. We prove the monotonicity and subadditivity of the FH-MDP, such that the FH-MDP has an optimal, monotone deterministic Markovian policy. We find that the optimal policy consists of flight distance-related and time-related thresholds at which the optimal action of the UAV switches. As a result, the optimal actions of the UAV can be obtained by comparing its state with the thresholds at a linear complexity.

- This thesis presents a novel multi-task UAV routing framework, which aims to minimize the UAV's energy consumption, maximize its sensing reward, and ensure its timely arrival at the destination. We interpret possible flight waypoints as location-dependent tasks, hence accommodating the waypoints and in-situ sensing in a unified process of task selection. We construct a weighted time-task graph, and transform the optimal routing of the UAV to a weighted routing problem, which can be optimally solved by the celebrated Bellman-Ford algorithm.

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List of Publications

Journal Papers

J-1. **B. Liu**, W. Ni, R. Liu, Q. Zhu, Y. J. Guo, and H. Zhu. "Novel Integrated Framework of Unmanned Aerial Vehicle and Road Traffic for Energy-Efficient Delay-Sensitive Delivery," *IEEE Transactions on Intelligent Transportation Systems*, Early Access 2021. (Chapter 3).

J-2. **B. Liu**, W. Ni, R. Liu and H. Zhu. "Optimal Selection of Heterogeneous Network Interfaces for High-Speed Rail Communications," *IEEE Transaction on Vehicular Technology*, vol. 69, no.12, pp. 15005-15018. 2020.

J-3. **B. Liu**, W. Ni, R. Liu, Y. J. Guo, and H. Zhu. "Optimal Control of Multi-Task Drone for Delay-Aware Goods Delivery and In-Situ Sensing," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Submitted 2021. (Chapter 4).

J-4. **B. Liu**, W. Ni, R. Liu, Y. J. Guo, and H. Zhu. "Optimal Routing of Unmanned Aerial Vehicle for Joint Goods Delivery and In-situ Sensing," *IEEE Transactions on Intelligent Transportation Systems*, under major revision (revised and resubmitted), 2021. (Chapter 5).

J-5. **B. Liu**, Q. Zhu, and H. Zhu. "Trajectory optimization and resource allocation for UAV-assisted relaying communications," *Wireless Networks*, vol. 26, no. 1, pp. 1–11, Nov. 739-749, 2019.

J-6. **B. Liu**, Q. Zhu, and H. Zhu. "Rotman lens-based two-tier hybrid beamforming for wideband mmWave MIMO-OFDM system with beam squint," *EURASIP Journal on Wireless Communications and Networking*, vol.2018, no.1 pp.267, 2018.

Conference Papers

C-1. **B. Liu**, W. Tan, H. Hu, and H. Zhu. "Hybrid beamforming for mmWave MIMO-OFDM system with beam squint," *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Bologna, Italy, Sept. 2018, pp. 1422–1426.

C-2. **B. Liu**, Q. Zhu, and H. Zhu. "Delay-Aware LTE WLAN Aggregation for 5G Unlicensed Spectrum Usage," *IEEE 85rd Vehicular Technology Conference (VTC Spring)*, Sydney, Australia, Jun. 2017, pp. 1-6.

Contents

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Abbreviation

3GPP: 3rd Generation Partnership Project

BS: Base Station

CAV: Connected and Automated Vehicle

DP: Dynamic Programming

FAA: Federal Aviation Administration

ILP: Integer Linear Programming

IoT: Internet of Things

ITS: Intelligent Transportation Systems

LoRaWAN: Long Range Wide Area Network

LoS: Line-of-Sight

MDP: Markov decision process

POI: Places of Interest

SWIPT: Simultaneous Wireless Information and Power Transfer

UAV: Unmanned Aerial Vehicle

VRP: Vehicle Routing Problem

WPT: Wireless Power Transfer

WSN: Wireless Sensor Network