氏　　名	Florence HO
学位（専攻分野）	博士（情報学）
学位記番号	総研大甲第 2192 号
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学位授与の要件	複合科学研究科　情報学専攻 学位規則第6条第1項該当
学位論文題目	Scalable Conflict Detection and Resolution Methods for Safe Unmanned Aircraft Systems Traffic Management
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(Form 3)

Summary of Doctoral Thesis

Name in full Florence HO

Title Scalable Conflict Detection and Resolution Methods for Safe Unmanned Aircraft Systems Traffic Management

The increasing demand for services performed by Unmanned Aerial Vehicles (UAVs), also called "drones", requires the conception of an Unmanned Aircraft System Traffic Management (UTM) system to ensure the safety and the efficiency of UAV operations in shared low altitude airspace. For this purpose, Conflict Detection and Resolution (CDR) methods that will resolve conflicts, i.e. predicted collisions, between UAVs need to be designed and developed.

In particular, the conception and deployment of a UTM system has recently prompted research on a multi-layered architecture. Two main layers can be distinguished: Pre-Flight CDR whereby conflicts are solved before UAVs takeoff by processing their submitted flight paths beforehand, and In-Flight CDR whereby conflicts are solved in real time when UAVs are flying, in case of unexpected events.

In this research, we explore the conception and development of methods for these two layers. Pre-Flight CDR and In-Flight CDR are complementary methods as defined by the International Civil Aviation Organization's (ICAO) conflict management layers. They are two distinct processes with different properties. Pre-Flight CDR allows for longer conflict detection and resolution look-ahead times, it is not time critical and thus can use sophisticated resolution capabilities that can prevent and mitigate downstream conflicts. With Pre-Flight CDR methods, it is thus possible to determine globally optimal solutions in terms of costs like delays for each UAV. In contrast, In-Flight CDR is more time critical as UAVs continuously move while processing. Thus, the conflict-free solutions obtained are locally optimal with respect to costs like delays, as In-Flight CDR focuses on resolving an incoming conflict detected within a look-ahead time window, and then do not necessarily prevent downstream conflicts from occurring.

Hence, they require different types of resolution methods to satisfy their respective properties. The methods used for In-Flight CDR would not be appropriate for Pre-Flight CDR and vice versa. Therefore, this thesis is divided into two distinct research parts, one for each phase, In-Flight CDR and Pre-Flight CDR.

Our research makes several contributions as follows:

- First, we propose a scalable In-Flight CDR method based on Optimal Reciprocal Collision Avoidance (ORCA). ORCA is a state-of-the-art collision avoidance algorithm mainly used in a limited theoretical scope, for pedestrian simulations and ground robots. Thus, it does not address practical considerations that are

necessary to the deployment of UAVs in shared airspace, such as navigation inaccuracies, communication overhead, and flight phases. Therefore, we extended the method to In-Flight CDR for UAVs, by including an advanced conflict detection mechanism to improve ORCA's scalability, and uncertainty parameters to address navigation inaccuracies.

We evaluated our approach through simulations. First, by empirically tuning the considered ORCA parameters, we reduced the generated deviations from the initial flight path. Second, by simulating realistic UAV traffic for delivery, we determined a value for separation distance between UAVs that uses airspace efficiently.

- Second, we propose a scalable Pre-Flight CDR method based on Enhanced Conflict-Based Search (ECBS). We address the Pre-Flight CDR problem by introducing a mapping to Multi-Agent Path Finding (MAPF), and we extend state-of-the-art MAPF algorithms to take into account the practical requirements of the UTM context. MAPF approaches have mostly been applied to solve comparable problems with ground robots. However, they were tested with simplifying assumptions that do not reflect important characteristics of many real-world domains, such as delivery by UAVs.

  Therefore, we introduced a novel mapping to the UAVs case, that considers 3D space, heterogeneous agents with different sizes and speeds, and ongoing processing of UAV operation requests. We proposed a new method for conflict detection based on geometrical computations to address heterogeneous agents and improve the scalability of our method. Moreover, we addressed the ongoing processing of operation requests by proposing a "batch" processing based on ECBS and a First-Come First-Served (FCFS) processing based on the Cooperative A* algorithm. We performed simulations based on a study on UAV usage predicted for 2030 in Sendai in Japan. For peak hour scenarios, batch processing proved more efficient, with a better throughput than FCFS processing. Thus, it is able to meet the requirements of timely and accurate response on delivery requests to users of such UTM services.
- Further for Pre-Flight CDR, we propose an extension of the MAPF model based on negotiation that allows several independent UAS Service Providers (UASSPs) to resolve the existing conflicts between their given UAV operations according to their individual costs in a decentralized way. UASSPs are independent entities, each with their own group of UAVs, and they will provide services, such as de-confliction services, to UAS operators who submit UAV operations (flight paths) requests from customers. Recent discussions on UTM suggest that such centralized control might not be practical or desirable, and this may result in an "unfair" distribution of induced costs in terms of delays caused by conflict resolution among UASSPs. In this context, Pre-Flight CDR must support the

decentralized resolution of conflicts, whereby self-interested "agents" (UASSPs) communicate with each other to resolve conflicts among their UAV operations, with their own business objectives to maintain a certain service quality or satisfy operational constraints. Therefore, we propose a suitable approach based on a negotiation method to allow several UASSP agents to bargain between them a conflict-free solution for their UAV operations, whereby they agree on their individual costs computed in function of total delays and so on.

- Finally, we consider another extension for Pre-Flight CDR, whereby we introduce scheduling techniques, i.e. time-based resolution, into the MAPF model to improve the performance of Pre-Flight CDR methods. The standard MAPF formulation provides limited assumptions whereby UAV agents' start times are fixed and apply a uniform speed on their path. Therefore, we hereby propose to relax those assumptions to improve the efficiency of MAPF solvers in particular in high density structured airspace. We introduce two methods for conflict resolution based on temporal resolution, that are takeoff scheduling and speed scheduling. We propose to combine different conflict resolution techniques in an informed manner, unlike standard MAPF solvers that use path re-planning by default. For this purpose, we introduced a conflict type distinction into the conflict detection step of the ECBS algorithm that allows to determine the most efficient resolution technique to be applied depending on the conflict type detected. This extension allows to reduce the generated delays of the obtained solutions and the number of rejected UAV operations.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名　　Florence HO

Title
論文題目　　Scalable Conflict Detection and Resolution Methods for Safe Unmanned Aircraft Systems Traffic Management

The applicant has submitted this thesis for a determination of whether it is worthy of the awarding of a degree. The decision by the panel will be based on the following.

This thesis is titled "Scalable Conflict Detection and Resolution Methods for Safe Unmanned Aircraft Systems Traffic Management".

The Introduction explains that he thesis work addresses two out of three conflict management layers ("collision avoidance"), as defined by the International Civil Aviation Organization (ICAO), and applies it to Unmanned Aerial Vehicles (UAVs), or drones:

- Strategic Conflict Management, or Pre-Flight Conflict Detection or Resolution (CDR)
- Separation Provision, or In-Flight CDR
- Sensor-based Detect and Avoid (DAA) methods: these are not part of the thesis, as they do not contain any element of optimization

Thus, the context of the thesis is Unmanned Aircraft System Traffic Management (UTM), where UAVs operate in shared low-altitude airspace.

Chapter 1 describes In-Flight CDR. It is the first time that the Optimal Reciprocal Collision Avoidance (ORCA) was adapted to the practical considerations of UTM. Basically, ORCA computes half-planes of conflict-free velocities for each UAV A with respect to all other UAVs B1,...,Bn. Then ORCA outputs optimal (minimal deviation) collision-free velocities for each UAV using linear programming. The main contribution was to address the practical (real-world) requirements of In-Flight CDR for UAVs, such as communication overheads and UAV navigation inaccuracies. A conflict detection filtering step was included to increase scalability. Future work is also described in this chapter.

Chapter 2 describes centralized Pre-Flight CDR. It is the first time that it was conceived as a Multi-Agent Path Finding (MAPF) problem. Unlike existing approaches, we consider scenarios in 3D, with heterogeneous agents, ongoing processing (e.g., delivery service by drone). The underlying method of MAPF used for Pre-Flight CDR is Conflict-Based Search (CBS). CBS alternates between two phases: (i) High-level search, where the method detects conflicts between pairs of agents and adds constraints, and (ii) Low-level search, where the method creates agents' paths that satisfy all constraints by single-agent path planning. To increase scalability to high numbers of UAV operations (e.g. delivery operations), the MAPF method has been adapted in two major ways.

- We incorporate geometrical computations to increase the efficiency of the conflict detection (CD) step of MAPF. This method outperforms standard grid cell-based methods.
- We introduce batch processing to increase the throughput of processed operations in peak times of UAV operation demand. This method outperforms standard "First-come First-served" (FCFS) methods.

Chapter 3 describes our experiments with centralized Pre-Flight CDR on the Sendai 2030 model case, which describes a projection of delivery by drone in Sendai in 2030.

Chapter 4 describes decentralized Pre-Flight CDR. A recent requirement for Pre-Flight CDR is that in the pre-flight phase, so-called "Unmanned Aircraft System (UAS) Service Provider (UASSP)" agents communicate in a decentralized fashion to de-conflict their respective fleets of UAV operations. To accommodate for this requirement, the MAPF method was extended in a novel way to support negotiation between UASSP agents. Besides scalability, "fairness" between UASSP agents becomes an important metric. Fairness on the UASSP level means that there exists a balanced distribution of "costs" (delays of operations, rejected operations) between UASSP agents. Through simulations, we could demonstrate that our negotiation-based Pre-Flight CDR method leads to more fairness than a method without negotiation.

Chapter 5 describes a scheduling approach to Pre-Flight CDR, and discusses future works for Pre-Flight CDR.

The work on In-Flight CDR was published in the *IEEE Transactions on Vehicular Technology* in 2019. The work on centralized Pre-Flight CDR was published in the *Proceedings of the 18th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2019)*. Some extensions of this work, targeting a more general audience, have been published in the *IEEE Access* journal. The work on decentralized Pre-Flight CDR is currently under second review after revision to the *IEEE Transactions on Intelligent Transport Systems*.

At the public presentation, Florence HO presented her thesis work for 45 minutes in an online meeting on July, 15, 2020. Then a Q&A session was held with the thesis Evaluators. Ms. HO was able to answer all questions in a satisfactory way.

After the Q&A session, a review committee was held among the Evaluators. In this meeting, the Evaluators judged that this thesis was worthy of the awarding of the degree.