Trajectory Planning Techniques in Urban Air Mobility: A Comparative Survey

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ABSTRACT

New prospects for on-demand air mobility, business proposals, and airship blueprints are rapidly emerging due to the advancement in electrification, automation, and other technology. Owing to the recent development of manned and unmanned flying vehicles, the low altitude transportation services in urban areas can help to mitigate the traffic congestion. As a result, the technology of urban air mobility (UAM) provides a safe, affordable, and faster aerial transport system for the movement of passengers, the flexible delivery of goods, and the provision of emergency services into or through metropolitan areas. Considering the complex city environments including high-rise buildings, numerous manned and unmanned aerial vehicles, and restricted areas, designing the optimal trajectory for UAM operation is a very challenging task. Proper trajectory planning and vehicle scheduling can reduce the flight travel time and fuel cost. In this paper, we survey recent trajectory planning techniques for seamless transition in UAM operations. The techniques are qualitatively compared in terms of key characteristics, advantages, and limitations. We also discuss important open issues and research challenges.

KEYWORDS

Air traffic management, on-demand air mobility, unmanned aircraft system, urban air mobility, trajectory planning, vertical take-off and landing

1 INTRODUCTION

Recently, there has been an increasing demand for optimized public services in urban environments in order to deliver better services to people living in cities. Different service divisions combine the concept of smart city such as smart transportation, smart mobility, and smart surveillance. Here, one vital service segment for humanity is transportation. Owing to the increase in population density in urban areas, ground transportation in big urban cities have been facing several challenges such as resilience and congestion. The ground traffic control system is exhausted because limited road capacity and continuous increment in the number of ground vehicles. Expanding the underground transportation capacity is time consuming. Additionally, based on the geographical location in some countries, it is extremely difficult to expand underground transportation capacity. Throughout the world, smart cities are experimenting with unmanned aerial vehicles (UAV) to prevent the expansion of the COVID-19 pandemic, such as: 1) monitoring and enforcing social distancing and providing public announcements to use protective equipment; 2) virus detection; 3) delivering the goods and emergency medical supplies; and 4) disinfecting the contaminated areas. Although the global pandemic has the possibility to increase public familiarity with UAVs, some people have showed anxieties about maintaining the privacy, civil rights, safety, and effectiveness to achieve desired health issues due to the noise produced by the aerial vehicles.

Industry and academia have devoted resources in recent times to develop a new concept to expand urban transportation such as the conception of a new smart air transportation system. This latest paradigm comprises the urban air mobility (UAM) concept, in which humans and goods are transported around metropolitan areas utilizing the low altitude airspace environment. As a result, UAM has been proposed to enhance the transportation systems using manned and unmanned aerial vehicles. Additionally, a variety of technological enhancements in automation, navigation system, control system, battery technology, and vertical take-off and landing (VTOL) are enabling innovations in urban aeronautics including new aircraft designs, services, and trajectory planning. Especially, the VTOL features enable autonomous vehicles to fly in a confined area avoiding external obstacles. In addition, the electric aerial vehicles are environment friendly. Nevertheless, safety is one of the major concerns considering the usage of these new technologies. Moreover, although autonomous vehicles can be beneficial to transportation, a presently encountered challenge is the social recognition of these technologies.

Several companies are working on the expansion of UAM vehicles such as small rotary wing flying car and hybrid fixed wing UAVs with hovering capability [1]. The expected operational benefits of UAM are less travel time, the consistency of travel duration, and the expansion in transportation capacity. However, trajectory planning is a very challenging task due to several factors that affect UAM operations. Firstly, the trajectories must not cause collisions or lead the VTOL of vehicles to an unsafe state. For instance, it should not lead two VTOL vehicles very close to one another. The trajectory planning procedure must examine safety issues more precisely because the UAM processes are expected to include numerous vehicles following several trajectories. Secondly, UAM operations are supposed to take place in dense and dynamic urban environments. Thus, the presence of high-rise buildings and restricted areas should be considered. Especially, for flying over the residential areas at night, noise is a key concern. Thirdly, energy-efficient trajectory planning is necessary to reduce the cost of UAM operation. The proper planning of three-dimensional mapping is needed to design optimal route for the autonomous vehicles [2]. Finally, the trajectory of each route should be optimal in terms of travel distance to reduce the travel time and minimize the vehicle fuel cost. This enhances the trajectory planning process when maneuvers need to be accurately designed to avoid sudden collisions and unexpected situations. In addition, the optimal scheduling of vehicles is necessary to maximize the revenue [3,4]. decrease the passenger waiting time, and reduce the fuel cost. Figure 1 shows a prototypical future smart city with organized trajectory for seamless UAM operation.

Figure 1: A prototypical future smart city with organized trajectory for seamless UAM operation.

In this paper, we provide a comprehensive survey on the trajectory planning techniques in UAM. First, we provide a background study on UAM. Next, we discuss the different algorithmic approaches in UAM trajectory planning in the light of existing literature. We also draw a qualitative comparison for better understanding the ongoing trends in trajectory planning techniques in UAM. Key open issues and research challenges are also discussed to motivate further study in this field.

The remainder of this paper is organized as follows: In Section 2, we describe brief history, recent advancements in UAM industry, and motivation behind this survey. Section 3 provides different trajectory planning techniques in UAM. In Section 4, the techniques are qualitatively compared in terms of application area, main idea, algorithm, advantages, and limitations. In Section 5, we discuss the open issues and challenges associated with trajectory planning in UAM. Finally, the conclusion of this survey is drawn in Section 6.

2 BACKGROUND AND MOTIVATION

In this section, the background and motivation of this survey are described. The brief history of UAM, recent advancements in UAM, and motivation behind this survey are overviewed in brief.

2.1 Early History of UAM

Early notions of "flying automobiles," such as Glenn Curtiss' Autoplane, created in 1917 [5], sparked the creation of the first ancestors of UAM aircraft in the early 1900s. A few years later, Henry Ford started developing "plane cars" for a single person, but the project was failed to see the light of the day at early stages. The Berliner No. 5 was one of the earliest vertical-takeoff-and-landing aircraft (VTOLs) developed in 1924 [6]. Autogyros prototypes were created by combined collaboration of Pitcairn, Cierva, Buhl, and other companies [7]. The Avrocar, a military aircraft with a disk-shaped fuselage, was originally supported by the Canadian government. It was expecting to bring some breakthrough, but the project was scraped owing to expenses until the US Army and Air Force took control and later on the project was forced to drop due to the same issue [8].

2.2 Recent Advancement of UAM

Arrival of millennium, people started seeing the first sign of breakthrough in UAM technology as several aircraft manufacturers began incorporating tiny drone technology into new passenger aircraft designs. The Kitty Hawk Flyer was first developed in 2010 with funding from Larry Page, co-founder of Google [9]. Marcus Leng piloted the first manned flight on October 5, 2011 and later on developed a fixed-wing all-electric VTOL aircraft "BlackFly" [10]. In 2019, Lockheed Martin introduced the S-76B Sikorsky Autonomous Research Aircraft (SARA) [11]. In June 2021, Chinese autonomous aerial vehicle (AAV) giant EHang performed the AAV EHang216's first pilotless test flight in Japan [12]. In the same month, Volocopter exhibited a remote-controlled flight of their eVTOL, the Volocopter 2X, as well as the first public flight of an electric air taxi in France [13]. Joby accomplished a flight of their eVTOL in July 2021, covering 150 miles on a single battery charge [14].

2.3 Motivation

Leading industries, universities, and research institutes as well as municipalities have formed the Air Transportation Initiative under the direction of Airbus to contribute to the development of enhanced air mobility initiative (AMI) [15]. It is now a matter of time that UAM becomes a reality. Moreover, there can be heterogeneous types of UAM which will fly around the city. To achieve this goal, proper trajectory planning and waypoint selection are necessary to avoid any accidental circumstances and ensure seamless operation of UAM. On top of all these, the optimal route, fuel efficiency, and cost mitigation are important for both passengers and UAM service providers. There have been a few studies regarding to the trajectory planning of UAM in both scheduled and on-demand cases. Motivated by all these, we highlight the state-of-the-art trajectory schemes for seamless, energy-saving, and cost effective UAM operations.

3 TRAJECTORY PLANNING TECHNIQUES IN UAM

In this section, we review various existing trajectory planning techniques developed for UAM. Their main ideas, design principles, key features, and pros and cons are comprehensively investigated.

3.1 Wind-optimal Trajectory (WOT)

Considering the challenges in UAM such as the presence of strong wind, Pradeep et al. [16] proposed an optimal trajectory control problem. The authors deeply studied eVTOL model, flight dynamics, kinematic model, drag model, induced hovering velocity, forward flight momentum theory, power requirement, and path constraints. The problem is optimized both by direct method and by converting into non-linear program (NLP). Using an open-source platform PSOPT, the NLP problem is solved and the FACET tool aids modelling 4D trajectory paths. Using real-time data collected from Dallas-Fort Worth metropolitan area and New

York metropolitan area were chosen as simulation environment. The simulation results lead to identical wind-optimal trajectories for uniform wind condition. The study concludes that for short duration flight, windy condition has insignificant impact on energy consumption and flight trajectory.

3.2 Monte-Carlo Tree Search-Upper Confidence Bound for Trees (MCTS-UCT)

Based on the complexity in air traffic management comprising several electrical VTOL supported manned and unmanned aerial vehicles in urban confined areas, Yang et al. [17] designed a safe and effective on-demand free flights using Markov decision process. They designed a high-density free flight airspace simulator to examine their proposed method. Considering the free flight scenario, a computational guidance algorithm with collision avoidance ability was proposed to drive the aircraft to its destination. The designed method utilizes the MDP and the Monte Carlo Tree Search, in which the algorithm takes input the present position and velocity of other neighboring aircraft, and the destination of the controlling aircraft. According to the neighboring sensing information of other aircrafts, the controlled aircraft will execute online sequential decision making to choose actions in real time. The sequential actions will drive the aircraft to reach its destination with less travel time and collision avoidance. In their MDP problem formulation, the sate space defines the position and velocity status of all the surrounding aircrafts, and the action space defines the bank angle and acceleration of the controlled aircraft to find the optimal trajectory. The proposed method provides a cost-effective solution to facilitate autonomous on-demand free flight operations in UAM.

3.3 Particle Swarm Optimization-Genetic Algorithm-Greedy (PSO-GA-GREEDY)

Mobility on demand (MoD) is a new paradigm of personal mobility that provides the passengers' demands in real time, and UAM is an area of MoD enabled by advances in electric VTOL. This demand-responsive type of MoD creates a challenge for optimally scheduling vehicles, and it has attracted much interest in recent years. However, there is a lack of research in the MoD scheduling in the literature because most of the existing studies focused on homogeneous fleet, which is not accurate all the time. Motivated by these limitations, the authors in [18] proposed a novel MoD scheduling problem for a UAM with a heterogenous fleet. They used two heuristic algorithms (i.e., particle swarm optimization and genetic algorithm) combined with greedy algorithm to solve the MoD scheduling problem. The objective of their designed problem is to maximize the net profit under the constraint of limited seats in vehicles, the fixed number of aerial vehicles, and the limited waiting time of vehicles at each station. Simulation results showed the designed algorithm can solve the MoD scheduling problems with less computation time while maintaining the optimality in solution.

3.4 Rapidly Exploring Random Trees* (RRT*)

The work proposed in [19] has taken a page from the one of the popular path planning used for robotics. It is rapidly exploring random trees* (RRT*), a modified version of original RRT algorithm. In order to find vertiports during the flight for scheduled or emergency landing, the variants of ChooseParent and Rewire algorithms have demonstrated better result in terms of path quality and processing time. On top of that, RRT* algorithm was used for immediate path planning in order to avoid geofencing. In their work, they have also considered different wind conditions which is closer to the real-life scenarios. However, they have only considered forward mobility with constant velocity which they aim to improve and present a realistic trajectory planning as their future work.

3.5 Arrival Sequencing and Scheduling (ASS)

The new rising paradigm in UAM networks, the concept of operation (ConOps), has drawn a lot of attentions recently. The work in [20] is based on ConOps and considers a novel approach for scenarios where the landing of UAMs is constrained by limited battery level and vertiports for landing. Their algorithm's objective is to mitigate the arrival delay of UAM under the constraints of battery level, thrust, attack angle, flight path angle, pitch angle, hover velocity, and thrust per rotor. Keeping the ConOps paradigm in mind, arrival sequence and operation schedules of UAM are designed. GPOPS-II software was used for simulating trajectory of eVTOLs. Finally, an energy-optimal sequence of arrival at vertiports is computed using the CPLEX solver and optimal data are generated using MATLAB. As the major drawback of their work, the authors did not take weather and collision avoidance issues into consideration while designing the algorithm.

3.6 Automated Flight Planning System (AFPS)

The approach taken by the authors in [21] comprises proposal of automated flight planning system (AFPS), which is sub-divided into two sections: low-altitude airspace management system (LAMS) and low-altitude traffic management system (LTMS). LAMS aids the creation of 3D path planning and ensures collision avoidance. On the other hand, LTMS figures out energy-saving shortest flight path while considering different aircraft parameters. The LTMS scheme also involves further developing two other models which can be chosen as per requirement. Performance analysis of both models were compared in terms of flying time distribution, system cost, and computation time in different scenarios. Although this work has a sound background and work with real-time data, the impact of weather and collision avoidance on trajectory planning was overlooked.

4 COMPARISON

There are several parameters which are needed to be taken into consideration while making a sound trajectory planning for UAM. First and foremost, the safety of passengers must be taken into consideration which can be achieved by having a collision avoidance system. Collision can occur in between eVTOLs or generic obstacles such as buildings and poles. Secondly, devising energy efficient trajectory is an unspoken condition for UAM operation because UAM have limited energy. Efficient vertiport and waypoint selection in real world problem can defiantly save money as well as time for passengers. In short, proper trajectory planning must avoid geo-fences, have landing vertiports ready for charging and swapping batteries, be maintained by the air traffic management system. Table 1 summarizes the qualitative comparison of trajectory planning techniques in UAM in terms of application area, main idea. Algorithm, advantages, and limitations.

As shown in Table 1, each trajectory planning technique was designed for its own target environment and has distinctive characteristics. In WOT [16], the authors considered the real-world data from Dallas-Fort metropolitan and New York metropolitan areas to observe the impact of wind on energy consumption and trajectory. Although they considered various kinematics model and energy consumption model for the flight, they ignored the collision avoidance that is one of the major safety concerns of UAM operations. This issue is addressed in the work studied in [17], where a trajectory model with collision avoidance using Markov decision process (MDP) and Monte-Carlo tree search (MCTS) was developed. However, in the design, they did not consider the impact of weather. Also, the trajectory prediction model is not so accurate although the convergence rate is faster.

Table 1: Comparison of trajectory planning techniques in UAM

Technique	Target environment	Main Idea	Algorithm used	Advantages	Limitations
WOT [16]	Dallas-Fort Worth and New York metropolitan areas	Exploits the impact of wind on UAM energy consumption and trajectory in four-dimensional (4D) space.	Non-linear program (NLP)	Considers various design parameters to see the impact of wind on trajectory.	Collision avoidance mechanism was not considered in the study.
MCTS-UCT [17]	High density air traffic	Devises a collision-free trajectory planning for UAM operation with faster convergence.	Markov decision process (MDP) and Monte-Carlo tree search (MCTS)	Has reduced action space than ORCA algorithm (benchmark) without performance degradation. Increases the chance of collision avoidance by increasing uncertainty parameters.	Trajectory prediction is not accurate. Weather effect is not considered.
PSO-GA-GREEDY [18]	Heterogenous fleet	Devises a practical on-demand mobility trajectory and scheduling scheme, resulting in near optimal solution with minimum computation time.	Particle swarm optimization (PSO) and genetic algorithm (GE)	Demonstrates the relation between QoS and operational efficiency. Finds solution in short time.	Effect of weather and security features are not considered. MILP solvers using branch-and-bound method does not always guarantee convergence.
RRT* [19]	Urban airspace	Demonstrates a sampling-based trajectory scheme to find cost-optimal path planning with the capability of avoiding all geo-fences.	Rapidly exploring random trees* (RRT*)	Considers emergency landing scenarios and calculates new rapid route accordingly.	Only forward mobility with constant velocity is considered.
ASS [20]	Multi eVTOLs (EHANG 184)	Studies the mitigation arrival delay with respect to battery level of the eVTOL and designs energy-efficient arrival trajectory.	Mixed integer linear program (MILP)	Proposes multiple air routes and arrival of multiple vehicles. Arrival sequence considers battery discharge level of UAM.	Departure model and the effect of weather and wind are not studied.
AFPS [21]	Tampa bay area in Florida with 30 vertiports	Devises an automated flight planning system (AFPS) with collision avoidance, capable of ensuring collision-free trajectories in low altitude urban regions.	Mixed integer second-order cone program (SOCP)	Seamless automated airspace and traffic management system was designed and can be chosen based on user demand.	Impact of weather are not studied.

Another model considering faster convergence with the minimum computational time was studied in [18]. The proposed model is based on particle swarm optimization and genetic algorithm. Although the convergence rate is faster for this proposed model using MILP solvers such as brunch-and-bound, it does not always guarantee convergence. Therefore, researchers go further down the line for finding optimal trajectory plan. Inspired by robotic path planning, rapidly exploring random trees* (RRT*), a modified version of original RRT scheme was proposed in [19] to study trajectory in urban airspace. RRT* is a sampling-based trajectory scheme to find cost-optimal path planning with the capability of avoiding all geo-fences. In this work, the authors considered emergency landing scenario and predicting new optimal landing vertiport. However, their work focuses on forward mobility of UAM with constant velocity.

Keeping the delay and arrival sequence and schedule of eVTOL in mind, the authors in [20] proposed a MILP problem which calculates arrival sequence with respect to battery discharge level of UAM. However, they did not consider departure model and weather effect in problem formulation. In [21], the authors studied with real-time data from the Tampa Bay area in Florida, USA with 30 vertiports. They devised an automated flight planning system (AFPS) with collision avoidance system. Their model can be modified and chosen as the demand requires. The major drawback of this model is that it did not consider the impact of weather on trajectory planning. Each model has its own strength and weakness.

5 OPEN ISSUES AND RESEARCH CHALLENGES

Although there has been significant advancement in the trajectory planning techniques in UAM, there still remain challenges to match up with the real-life scenarios. They are discussed in brief for future research to have a realistic, secure, energy-efficient, and cost-effective path planning.

5.1 Effect of Weather

Weather has a significant impact on trajectory planning of UAM, which is often overlooked or not taken into consideration when devising trajectory of UAM. In most cases, traditional aircrafts can withstand harsh weather conditions, but that is not the case for UAM [22]. Atmospheric conditions such as high-speed wind, snowfall, and dust particles should be taken into design consideration. Moreover, weather condition is varied from time to time. During snowy weather, ice might get stuck on the rotor of UAM, which might disrupt the operation of UAM. Besides, the weather condition is not same over different geographic areas. Existing studies often overlook these factors while planning a risk-free trajectory scheme.

5.2 Air Traffic Management

UAM poses some difficulties that are now unsolvable with conventional air traffic management (ATM) methods [23]. ATM services are meant to control all types of flights for both commercial and military aircrafts. The commercial flights are supposed to provide secure passenger and container deportation between well-known airports whereas the military aircrafts serve and secure the country's airspace from enemy attacks and provide support to the ground troops. As the number of autonomous aircrafts increases, UAM will need a separate air traffic management or an adapted one which can tackle on-demand, high-volume, and short-range flights in close proximity to urban airspace, and can coexist with the current ATM. Because these autonomous aircrafts will be providing their services in densely populated urban airspaces, they are expected to run their operation with tighter and more secure rules than present ATM system. Any UAM traffic management system must also be able to handle unusual occurrences in a safe manner without jeopardizing the system's overall performance. In present days, FAA has taken the initiative and is working closely with National Aeronautics and Space Administration (NASA) to work on this issue. Additionally, FAA developed and shared version 1.0 of the UAM concept of operations (ConOps) with both domestic and international stakeholders in June 2020 [24].

5.3 Community Acceptance

Although UAM demonstrates limitless potential, it also generates significant noise, visual pollution, and the breach of privacy [25]. Designing vertiports and waypoints based on private properties and no-flying zone must be taken into consideration. A well-designed trajectory plan in UAM might be planned over the private property or over no-flying-zone such as military base. In reality, this cannot be implemented although the plan satisfies all other design parameters. Therefore, a well-balanced trajectory plan must consider the surroundings so that UAM implementation can be accepted by the people.

5.4 Security

With the advancement in the UAM technology, cyberattacks are also becoming emerging problem in this scene [26]. Various design aspects must consider safety and security of the VTOL traffic management for the sake of passengers. Cyberattacks can result in hijack control of the AAS, leading to loss control of the overall UAM network. Researchers need to focus on preventing such cyber-physical vulnerabilities and designing fail-safe and fail-secure system for seamless UAM operations.

6 CONCLUSIONS

In this paper, we have surveyed the trajectory planning techniques in UAM to provide readers with basic concepts, existing techniques, and challenging issues comprehensively. Although the purpose of UAM is to deliver safe, sustainable, economical, and accessible transportation, UAM confronts a number of obstacles including public acceptability, safety, and societal equality. Early UAM operations will certainly need significant cooperation and investment from both private and governmental sectors in order to build infrastructure and operations. Although UAM has a lot of potential to enhance the lifestyle in smart cities, it still requires proper planning, raising people awareness, and developing the endurance of the vehicles. Development in aerial vehicles and their optimal trajectory according to the task requirements can help to adopt this facility to enhance the transportation facilities in highly dense urban areas. In addition, proper planning and standard guideline are also required for the successful implementation of this next-generation transportation system.

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