eVTOL Arrival Sequencing and Scheduling for On-Demand Urban Air Mobility

eVTOL 到达序列与调度: 按需城市空中出行

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Abstract-Urban Air Mobility (UAM) has the ability to reduce ground traffic congestion by enabling rapid on-demand flight through three-dimensional airspace with zero operational emissions by using electric Vertical Take-Off and Landing (eVTOL) vehicles. In the long term with more UAM flights, air traffic control is expected to limit further growth of such operations. Therefore, a first research has been performed on energy-efficient trajectory optimisation for a given required time of arrival, as the arrival phase is the most safety-critical flight phase with much higher air traffic density and limited battery energy. However, research on the computation of the optimal required time of arrival (RTA) for eVTOL aircraft has not yet been performed. Unlike fixed-wing aircraft or helicopters in commercial aviation, eVTOL aircraft have different flight dynamics, limited battery energy supply and a limited number of landing spots at a vertiport such as the top of high-rise buildings. This work is the first to utilise a mixed-integer linear program that computes the optimal RTAs for eVTOLs to safely separate them for minimum delay based on remaining battery state of charge and vertiport capacity. A concept of operations for vertiport terminal area airspace design is also proposed while making use of the existing energy-efficient trajectory optimisation tool. The research serves as a basis for further development of safe and efficient UAM operations. The mathematical model can also be applied to Unmanned Aircraft System Traffic Management (UTM) by inserting new separation requirements and flight dynamics for smaller drones when optimising a high density arrival terminal airspace.

摘要-城市空中出行 (UAM) 有能力通过使用电动垂直起降 (eVTOL) 车辆在三维空域实现快速按需飞行，从而减少地面交通拥堵，并且实现零运营排放。从长远来看，随着更多的 UAM 航班，空中交通管制预计将限制此类操作的进一步增长。因此，已经对给定所需到达时间的能量高效轨迹优化进行了初步研究，因为到达阶段是飞行中最关键的安全阶段，此时空中交通密度较高且电池能量有限。然而，对于计算 eVTOL 飞机最优所需到达时间 (RTA) 的研究尚未进行。与商业航空中的固定翼飞机或直升机不同，eVTOL 飞机具有不同的飞行动力学，有限的电池能量供应以及如高层建筑顶部等 vertiport 的有限着陆点数量。这项工作是首次利用混合整数线性程序计算 eVTOL 的最优 RTA，以基于剩余电池电量和 vertiport 容量安全地分离它们以实现最小延迟。同时，还提出了一个利用现有能量高效轨迹优化工具的 vertiport 终端区域空域设计的运行概念。这项研究为进一步开发安全高效的 UAM 运营提供了基础。该数学模型还可以应用于无人机交通管理 (UTM)，在优化高密度到达终端空域时插入新的分离要求和小型无人机的飞行动力学。

Index Terms-Urban Air Mobility, on-demand, eVTOL, arrival, sequencing, scheduling

索引术语-城市空中出行，按需，eVTOL，到达，排序，调度

I. INTRODUCTION

I. 引言

Urban Air Mobility (UAM) is an envisioned air transportation concept, where innovative aircraft could safely and efficiently transport passengers and cargo within urban areas by rising above traffic congestion on the ground. "The convergence of technologies, and new business models enabled by the digital revolution, is making it possible to explore this new way for people and cargo to move within our cities," said Jaiwon Shin, NASA Associate Administrator for Aeronautics Research Mission Directorate. Companies such as Airbus, Bell, Embraer, Joby, Zee Aero, Pipistrel, Volocopter, and Aurora Flight Sciences are working with their battery vendors to build and test electric vertical takeoff and landing (eVTOL) aircraft to ensure that vehicle safety and energy efficiency become an integral part of people's daily commute. However, there is a lack of concept of operations (ConOps) and air traffic control tools to support safe and efficient UAM operations with these new eVTOL aircraft. In this paper, we focus on designing the optimal UAM arrivals by integrating airspace design/configuration, trajectory optimisation, eVTOL battery modelling and arrival scheduling to enable safe and efficient flight operations in on-demand urban air transportation.

城市空中出行 (UAM) 是一个设想的航空运输概念，在这个概念中，创新型的飞机能够安全高效地在城市区域内运输乘客和货物，通过升空来避开地面交通拥堵。NASA 航空研究任务总监 Jaiwon Shin 表示："技术的融合以及数字革命带来的新商业模式，使得探索这种城市内人员和货物移动的新方式成为可能。"像空客、贝尔、巴西航空、Joby、Zee Aero、Pipistrel、Volocopter 和 Aurora Flight Sciences 等公司正在与他们的电池供应商合作，制造和测试电动垂直起降 (eVTOL) 飞机，以确保车辆的安全性和能源效率成为人们日常通勤的一部分。然而，目前缺乏运营概念 (ConOps) 和空中交通控制工具来支持这些新型 eVTOL 飞机的安全和高效 UAM 运行。在本文中，我们专注于通过整合空域设计/配置、轨迹优化、eVTOL 电池建模和到达调度，来设计最优的 UAM 到达方式，以实现在按需城市空中交通中的安全和高效飞行运行。

Unlike the small drones that can take off and land almost anywhere in the UAS Traffic Management (UTM) framework, eVTOL vehicles of UAM operations need to take off from and land at vertiports. When UAM operations are expected to increase, one of the major emerging bottlenecks will be the limited number of vertiports and landing pads, which will create a denser arrival UAM traffic in the corresponding terminal airspace. Therefore, we believe UAM arrival is the most safety-critical flight phase due to high-density terminal traffic, low remaining battery energy on eVTOLs, and limited resource of vertiport landing pads.

与在无人机交通管理 (UTM) 框架下几乎可以在任何地方起飞和降落的小型无人机不同，UAM 运行的 eVTOL 车辆需要在垂直机场起飞和降落。随着 UAM 运行的预期增加，其中一个主要的新出现的瓶颈将是有限的垂直机场和着陆垫的数量，这将导致相应的终端空域中出现更密集的 UAM 到达交通。因此，我们认为 UAM 到达是最关键的飞行阶段，因为高密度终端交通、eVTOL 上剩余电池能量低，以及垂直机场着陆垫资源有限。

In this paper, we address the challenge of UAM arrival by developing an arrival sequencing and scheduling algorithm for multiple arriving eVTOL aircraft competing for limited terminal airspace and vertiport resources. Our approach is to formulate this problem as a mixed-integer linear program. We propose a ConOps for UAM terminal airspace design with multiple arrival fixes/routes. The objective is to minimise the total eVTOL arrival delay at the vertiport. Each eVTOL aircraft is constrained by its remaining battery energy and flight performance parameters. We provide an optimal required time of arrival (RTAs) to all the arriving eVTOLs, whose onboard avionics can then compute their energy-efficient optimal arrival trajectories using tools presented in [1], [2].

在本文中，我们通过开发一种到达序列和调度算法来解决城市空中交通 (UAM) 的到达挑战，该算法适用于多个抵达的电动垂直起降 (eVTOL) 飞机，它们争夺有限的终端空域和垂直港口资源。我们的方法是将该问题构建为一个混合整数线性规划问题。我们提出了一个针对 UAM 终端空域设计的概念操作 (ConOps)，其中包括多个到达修正/路线。目标是最小化垂直港口所有 eVTOL 飞机的总到达延误。每架 eVTOL 飞机都受到其剩余电池能量和飞行性能参数的约束。我们为所有抵达的 eVTOL 飞机提供了一个最优所需到达时间 (RTAs)，它们的机载航电系统可以使用 [1]、[2] 中介绍的工具计算它们节能的最优到达轨迹。

The remainder of this paper is as follows. In Section II we outline the current research on aircraft and eVTOL arrival sequencing and scheduling. In Section III we present our model for eVTOL arrival scheduling. A case study on the EHANG 184 eVTOL is discussed in Section IV. In Section V we provide conclusions and recommendations.

本文的其余部分如下。在第二部分，我们概述了当前关于飞机和 eVTOL 到达序列和调度的研究。在

第三部分，我们提出了 eVTOL 到达调度的模型。在第四部分，我们讨论了 EHANG 184 eVTOL 的一个案例研究。在 V 部分，我们提供了结论和建议。

II. RELATED LITERATURE

II. 相关文献

In recent years, several studies have been conducted for on-demand Urban Air Mobility (UAM), i.e., point-to-point air traffic operations that do not follow a pre-defined service schedule, as is the case of traditional commercial aviation. Most research efforts are focused on the current UAM concept definition, demand forecasting and vehicle design. In [3] the UAM concept is described in terms of certification needs, infrastructure, traffic management, operational challenges. [4] researches the nature of these challenges and quantifies their impact by performing a case study on Los Angeles, USA. The development of tools and analysis to support this investigation of near- to far-term evolution of UAM has been described in [5] by a study on the San Fransisco Bay Area, USA. Both [4], [5] simulate the passenger flight demand to perform their feasibility studies. A system-level model on the number of vehicles needed in the system to meet demand, the number of vehicles airborne at any given time, and the length of time vehicles may have to loiter before a landing pad has been developed in [6].

近年来，已经进行了几项关于按需城市空中出行 (UAM) 的研究，即点对点的空中交通运行，不遵循预先定义的服务时间表，这与传统商业航空不同。大多数研究工作都集中在当前 UAM 概念的定义、需求预测和车辆设计上。在 [3] 中，UAM 概念被描述为与认证需求、基础设施、交通管理和运营挑战相关。[4] 研究了这些挑战的本质，并通过对美国洛杉矶的案例研究来量化它们的影响。在 [5] 中，通过研究美国旧金山湾区，描述了支持 UAM 近期到远期演变调查的工具和分析的发展。[4]、[5] 都模拟了乘客飞行需求以进行其可行性研究。在 [6] 中开发了一个系统级模型，该模型涉及系统中需要的车辆数量、任何给定时间内空中的车辆数量以及车辆在降落坪前可能需要盘旋的时间。

One of the operational challenges for eVTOLs is the scheduling of arrivals at vertiports since eVTOLs are battery constraint and, thus, flight time in the final approach is restricted. Moreover, pre-scheduling is not possible since flights are performed on-demand. This also requires scheduling arrivals in real-time and absorbing delays while airborne. For commercial aviation, a significant amount of research has addressed the problem of aircraft arrival sequencing and scheduling [7]-[9], with the objective, for instance, of minimising delay [10]-[13], cost or environmental impact [14], [15]. Such problems are constrained by, for instance, feasible landing time, time-based separation requirements, runway capacity [10] and airline preferences [16], [17]. Some of the frequently used methods to solve the aircraft arrival scheduling problem are position shifting [18], dynamic programming [17], [19], branch-and-bound [10], branch-and-price [12] and data-splitting [20], [21]. These methods are also combined with heuristics [22]. None of the models, however, are constrained to airport (e.g. gate) capacity or remaining fuel, while this should be considered when modelling eVTOL arrivals. Current research on scheduling of eVTOL arrivals at a vertiport is, however, limited. In [1], [2] the arrival trajectory of eVTOLs is optimised for minimal energy consumption based on a given RTA for a multi-rotor and tandem-tilted wing eVTOL, the EHANG 184 and Airbus A^3 Vahana respectively. In [6] a study on airspace system demand is performed for a range of values that future separation requirements would need to take to support high-demand, high-tempo UAM operations. In [23] continuous eVTOL vehicle routing, departure and arrival scheduling for UAM is developed such that minimum separation is ensured and eVTOL traffic is integrated with existing air traffic.

eVTOLs 的一个运营挑战是安排在立体停车场的到达时间，因为 eVTOLs 受电池限制，因此，在最后进近阶段的飞行时间受到限制。此外，由于航班是按需执行的，因此无法进行预先调度。这还要求实时调度到达并吸收空中延误。在商业航空领域，大量研究已经解决了飞机到达顺序和调度问题 [7]-[9]，例如，目标是最小化延迟 [10]-[13]、成本或环境影响 [14]、[15]。此类问题受到诸如可行着陆时间、基于时间的分离要求、跑道容量 [10] 和航空公司偏好 [16]、[17] 等限制。解决飞机到达调度问题的常用方法包括位置移动 [18]、动态规划 [17]、[19]、分支定界 [10]、分支定价 [12] 和数据分割 [20]、[21]。这些方法还与启发式方法相结合 [22]。然而，这些模型均未受到机场 (例如，登机口) 容量或剩余燃料的限制，而在建模 eVTOL 到达时应该考虑这些因素。然而，目前关于在立体停车场调度 eVTOL 到达的研究还非常有限。在 [1]、[2] 中，基于给定的 RTA，为多旋翼和串联倾斜翼 eVTOL(EHANG 184 和 Airbus A^3 Vahana) 优化了 eVTOL 的到达轨迹，以实现最小能量消耗。在 [6] 中，对一系列未来分离要求需要采取的值进行了空中系统需求研究，以支持高需求、高节奏的 UAM 运行。在 [23] 中，开发了连续的 eVTOL 车辆路由、出发和到达调度，以确保最小分离，并将 eVTOL 交通与现有空中交通集成。

An important constraint for eVTOLs is the current electric battery technology. No battery models for eVTOL vehicles are available, but research on battery predictions for electric winged aircraft [24], [25] and drones [26] has been performed. These models create a voltage and state of charge profile based on a flight plan using an Equivalent Circuit Model (ECM) to check if the plan can be fulfilled. Also, the ECM parameters are determined by flight testing a 33% scale model of the Zivko Edge 540T aircraft and one battery cell of the DJI Phantom 3 Standard drone, respectively. Complementary to existing research on eVTOLs traffic management, this research develops an arrival sequencing and scheduling model for UAM that minimises total delay while considering the battery status of each eVTOL and flying energy-optimal trajectories where possible.

eVTOL 的一个重要约束是当前的电电池技术。目前还没有适用于 eVTOL 车辆的电池模型，但是已经对电动翼飞机 [24]、[25] 和无人机 [26] 的电池预测进行了研究。这些模型基于飞行计划使用等效电路模型 (ECM) 创建电压和充电状态轮廓，以检查计划是否可以完成。此外，通过飞行测试 Zivko Edge 540T 飞机的 33% 比例模型和 DJI Phantom 3 Standard 无人机的单个电池单元，分别确定了 ECM 参数。作为现有 eVTOL 交通管理研究的有益补充，本研究开发了一种 Arrival Sequencing 和调度模型，用于城市空中交通 (UAM)，在考虑每架 eVTOL 电池状态的情况下，最小化总延迟，并在可能的情况下飞行能量最优轨迹。

III. MODELLING APPROACH

III. 建模方法

In this section, we describe our model for eVTOL arrivals at one vertiport. The model consists of 4 parts: i) the concept of eVTOLs arrivals at a vertiport; ii) the flight dynamics model for an eVTOL equipped with one electric battery; iii) the electric battery model and iv) an optimisation model for eVTOL arrival sequencing and scheduling at a vertiport.

在本节中，我们描述了我们的模型，该模型用于一个直升机场的 eVTOL 抵达。模型包括 4 个部分:i) eVTOL 在直升机场抵达的概念；ii) 配备有一个电动电池的 eVTOL 的飞行动力学模型；iii) 电动电池模型；iv) 直升机场 eVTOL 抵达排序和调度的优化模型。

A. eVTOL Arrivals at A Vertiport - Concept of Operations

A. eVTOL 在直升机场的抵达 - 操作概念

We consider eVTOLs arriving at one landing platform, i.e., a vertiport. Moreover, the eVTOLs operate in a segregated airspace volume and at a frequency of maximum 40 arrivals/hr [23]. We assume a total cruise phase of 25 minutes and altitude 500 m [27] with the final approach at a vertiport defined as follows. We also assume 2 arrival and 2 departure metering fixes at the vertiport [18] (see Fig. 1). These metering fixes have the purpose of separating climbing and descending traffic.

我们考虑电子垂直起降飞行器 (eVTOLs) 抵达一个着陆平台，即垂直机场。此外，eVTOLs 在隔离的空域体积内运行，频率最高为每小时 40 次抵达 [23]。我们假设总巡航阶段为 25 分钟，高度 500 m [27]，在垂直机场的最终进近阶段定义如下。我们还假设在垂直机场有 2 个抵达和 2 个出发流量控制点 [18](见图 1)。这些流量控制点的目的是分离上升和下降的流量。

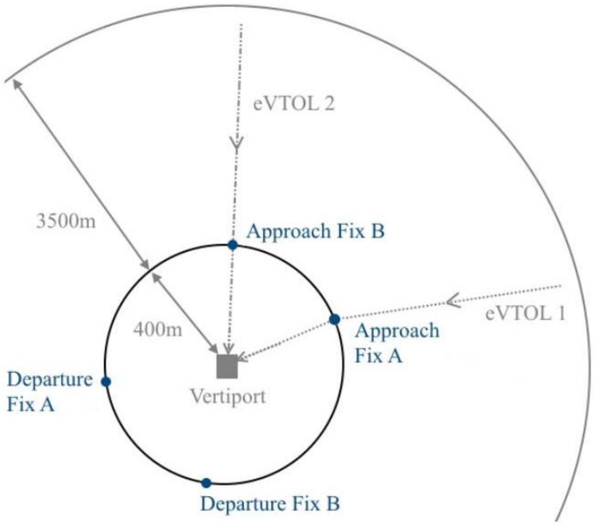

Fig. 1. eVTOL arrivals at a vertiport - concept of operations.
图 1. eVTOL 在垂直机场的抵达 - 操作概念。

The arrival approach fixes are located at a radius of 400 m away from the vertiport. A minimum time separation of 90 s [13] is assumed for the eVTOLs arriving at the 2 approach fixes. Furthermore, their required altitude at the approach fix is set to 200 m . This requirement is needed to ensure clearance from high rise buildings, as well as to provide sufficient space to absorb delay through shallow descent paths [1]. Between the approach fix and the vertiport, each eVTOL flies at a predefined speed and altitude profile (see Fig. 2), while maintaining a separation of 90 s between consecutive arrivals. This last phase of the trajectory is a step-down approach, which is considered to be efficient in minimising delay [28] and beneficial for clearance from high rise buildings.

到达进近控制点位于距离垂直机场 400 m 的半径处。假设抵达两个进近控制点的 eVTOLs 之间有最小时间间隔 90 s [13]。此外，它们在进近控制点所需的高度设置为 200 m 。这一要求是为了确保与高层建筑之间的间隔，以及提供足够的空间通过浅降路径吸收延误 [1]。在进近控制点和垂直机场之间，每架 eVTOL 以预定义的速度和高度剖面飞行 (见图 2)，同时保持连续抵达之间的 90 s 间隔。轨迹的最后阶段是逐级下降进近，这被认为是在最小化延误 [28] 方面效率高，并且有利于与高层建筑保持间隔。

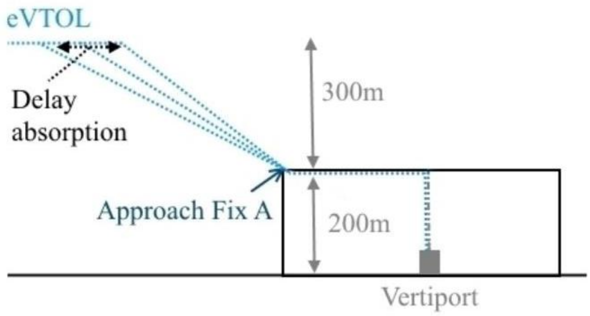

Fig. 2. eVTOL arrivals at a vertiport through approach fix A - side view.
图 2. eVTOL 通过进近控制点 A 抵达垂直机场 - 侧视图。

We assume that the arrival sequencing and scheduling of incoming eVTOLs is initiated at 3900 m radius around the vertiport (see Fig. 1). This radius has been determined based on a trade-off between maximising shallow descent flights and minimising the duration of approach procedures. This proposed ConOps allows for the absorption of delay up to 3 minutes without applying holding or vectoring.

我们假设，抵达序列和即将到来的 eVTOLs 的调度是从距离垂直机场 3900 m 半径处开始的 (见图 1)。这个半径是基于最大化浅降飞行和最小化接近程序持续时间之间的权衡确定的。这个提议的 ConOps 允许在不应用等待或向量引导的情况下吸收最多 3 分钟的延误。

B. eVTOL Flight Dynamics Model

B. eVTOL 飞行动力学模型

We use the following flight dynamics model for an eVTOL equipped with one electric battery [1].

我们为配备一个电动电池的 eVTOL 使用以下飞行动力学模型 [1]。

$$P_r = P_i + P_a + P_c + P_f \tag{1}$$

$$= 4 \cdot T \cdot v_i + T \cdot V \cdot \sin(\alpha) + 0.2 \cdot P_r \tag{2}$$

$$V = \sqrt{V_x^2 + V_h^2} \tag{3}$$

$$\alpha = \theta + \gamma = \theta + \arctan\left(\frac{V_x}{V_h}\right) \tag{4}$$

$$v_h = \sqrt{\frac{T_r}{2\rho\pi R^2}} \tag{5}$$

$$v_i = \frac{v_h^2}{\sqrt{(V \cdot \cos(\alpha))^2 + (V \cdot \sin(\alpha) + v_i)^2}}, \tag{6}$$

where P_r, P_i, P_a, P_c, P_f are the required, induced, parasite, climb and profile power, respectively, with $P_f = 0.2P_r$ [29]. V is the true airspeed with the vertical component V_x and the horizontal component $V_h.T, P, \alpha, \theta, \gamma$ are the thrust, the battery power, the angle of attack, the pitch angle and flight path angle, respectively. v_i, v_h, R, T_r, ρ are the induced velocity, the induced velocity in hover, rotor radius, thrust per rotor and the air density, respectively. ρ is assumed to be equal to the international standard atmosphere density at sea level.

其中 P_r, P_i, P_a, P_c, P_f 分别是所需的、诱导的、附加的、爬升和剖面功率，$P_f = 0.2P_r$ [29]。V 是真空气速，其垂直分量为 V_x ，水平分量为 $V_h.T, P, \alpha, \theta, \gamma$ 分别是推力、电池功率、攻角、俯仰角和飞行路径角。v_i, v_h, R, T_r, ρ 分别是诱导速度、悬停时的诱导速度、旋翼半径、每个旋翼的推力以及空气密度。ρ 假定等于国际标准大气在 sea level 的密度。

We further assume that all rotors produce equal thrust. Thus, we assume an upper and lower rotor to produce equal thrust [30], such that $T_r = \frac{1}{8}T$. The induced velocity v_i is computed using Momentum Theory and v_h , leading to (6). A fourth-degree polynomial arises when computing v_i , which is solved using the MATLAB Roots package [31].

我们进一步假设所有旋翼产生相等的推力。因此，我们假设上旋翼和下旋翼产生相等的推力 [30]，即 $T_r = \frac{1}{8}T$ 。诱导速度 v_i 使用动量理论计算，并且 v_h ，导致 (6) 式。在计算 v_i 时会出现四次多项式，使用 MATLAB Roots 包 [31] 求解。

C. Battery Discharge Model

C. 电池放电模型

We consider the following model for the total electric power demand, P_d, [26] , [32] :

我们考虑以下总电功率需求 P_d, [26] , [32] 的模型:

$$P_d = SF \cdot \frac{1}{\eta_P} \frac{1}{\eta_e} P_r \tag{7}$$

where SF is the safety factor to account for weather conditions and emergency diversion, $SF = 1.5, \eta_P$ is the rotor efficiency, $\eta_P = 0.7652, \eta_e$, is the mechanical efficiency, $\eta_e = 0.85$.

其中 SF 是安全系数，用于考虑天气条件和紧急改航，$SF = 1.5, \eta_P$ 是旋翼效率，$\eta_P = 0.7652, \eta_e$ 是机械效率，$\eta_e = 0.85$ 。

We further consider the following model for the battery State of Charge (SOC) during a mission [32]:

我们进一步考虑了在任务过程中电池荷电状态 (SOC) 的以下模型 [32]:

$$I(t_k) = \frac{P_d(t_k)}{V_n} \tag{8}$$

$$SOC(t_k) = SOC(t_{k-1}) - \frac{I(t_k) \cdot (t_k - t_{k-1})}{3600 \cdot Q}, \tag{9}$$

where $I(t_k)$ is the total current of all battery cells at time step t_k, V_n is the nominal battery voltage, Q is the battery capacity. The battery is assumed to be empty if the voltage is below 12 V or if it reaches a 0% SOC.

其中 $I(t_k)$ 是在时间步 t_k, V_n 上的所有电池单元的总电流，Q 是电池的标称电压，12 V 是电池容量。假设如果电压低于 12 V 或电池达到 0% SOC，电池为空。

D. eVTOL Arrival Sequencing and Scheduling Model

D. eVTOL 到达顺序与调度模型

Using the ConOps for eVTOLs arrivals at a vertiport in Section III-A, the flight dynamics model for an eVTOL in Section III-B and the eVTOL battery model in Section III-C, we propose an optimal sequencing and scheduling algorithm for eVTOL arrivals at a vertiport (see Fig. 3).

使用第 III-A 节中的 eVTOL 到达操作概念 (ConOps)，第 III-B 节的 eVTOL 飞行动力学模型和第 III-C 节的 eVTOL 电池模型，我们为 eVTOL 在立体港口的到达提出了一个最优顺序和调度算法 (见图 3)。

Firstly, using the ConOps for eVTOLs arrivals (Section III-A) and the eVTOL flight dynamics (Section III-B), we determine the optimal flight trajectory with respect to energy consumption for a given RTA at the vertiport [1], [2]. The optimal trajectories are computed using the GPOPS-II software [33]. The rotorcraft equations of motion are continuous-time nonlinear differential equations, such that the trajectory opti-misation problem is solved numerically using a pseudospectral method. This method transcribes a multi-phase optimal control problem to a large sparse nonlinear programming problem. The output of the GPOPS-II optimisation is the total energy required to fulfil the trajectory, the state variables (V_x, V_h , altitude and distance) and the control variables (T and θ) .

首先，使用第 III-A 节的 eVTOL 到达操作概念和第 III-B 节的 eVTOL 飞行动力学，我们为给定立体港口的预定到达时间 (RTA) 确定了最优飞行轨迹，以降低能耗 [1]，[2]。最优轨迹是使用 GPOPS-II 软件 [33] 计算的。旋翼飞行器的运动方程是连续时间非线性微分方程，因此轨迹优化问题通过伪谱法数值求解。这种方法将多阶段最优控制问题转化为大型稀疏非线性规划问题。GPOPS-II 优化的输出是完成轨迹所需的总能量，状态变量 (V_x, V_h (包括速度、高度和距离) 以及控制变量 (T and θ) 。

Secondly, we use the GPOPS-II optimisation output to determine P_r at each instance of the flight trajectory (see Section III-B). Further, P_r is used to determine the battery power demand P_d and the SOC demand (see Section III-C). The latest possible RTA is now found for each arriving eVTOL based on its battery status.

其次，我们使用 GPOPS-II 优化输出来确定 P_r 在飞行轨迹的每个实例上 (参见第 III-B 节)。进一步地，P_r 用于确定电池功率需求 P_d 和 SOC 需求 (参见第 III-C 节)。现在，基于每个到达的 eVTOL 的电池状态，找到可能的最新 RTA。

Thirdly, we determine an eVTOL arrival sequence and schedule at a vertiport for minimal total arrival delay. Equation (10) shows the objective function for minimum total delay for all eVTOLs p in set G , where G is the set of all eVTOLs considered, c_e^p and c_l^p are the cost of eVTOL p being earlier and later than $ETA^p(i)$ at approach fix $i \in \{A, B\}$, respectively. Here, $ETA^p(i), i \in \{A, B\}$, is obtained from the most energy-optimal trajectory.

第三，我们确定 eVTOL 的到达顺序和机场的调度，以最小化总到达延误。方程 (10) 显示了所有 eVTOL p 在集合 G 中的最小总延迟目标函数，其中 G 是考虑的所有 eVTOL 的集合，c_e^p 和 c_l^p 分别是 eVTOL p 在进近定位点 $ETA^p(i)$ 提前和延迟的成本。$ETA^p(i), i \in \{A, B\}$ 是从最节能轨迹获得的。

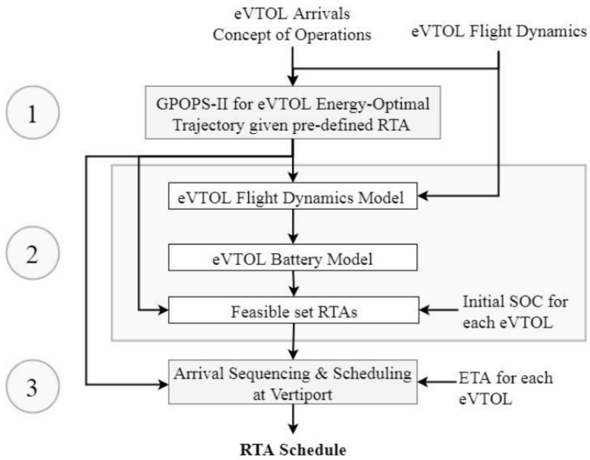

Fig. 3. eVTOL arrival sequencing and scheduling model overview.

图 3. eVTOL 到达顺序和调度模型概述。

We consider the decision binary variables $a^p, b^p \in \{0,1\}$, where $a^p = 1$ means that eVTOL p uses approach fix A and $a^p = 0$ otherwise; $b^p = 1$ means that eVTOL p uses approach fix B and $b^p = 0$ otherwise; $a^p + b^p = 1$. Also, the decision variables Δt_e^p and Δt_l^p describe the time that eVTOL p arrives before and after $ETA^p(i)$, respectively, at the approach fix $i, i \in \{A, B\}$. The delay resulting from choice of arrival route $\Delta t_{l,i}^p, i \in \{A, B\}$, is calculated by (11) and (12) in which T_t^p is the transfer time of flight between the approach fix and vertiport.

我们考虑决策二进制变量 $a^p, b^p \in \{0,1\}$ ，其中 $a^p = 1$ 表示 eVTOL p 使用进近定位点 A，$a^p = 0$ 否则；$b^p = 1$ 表示 eVTOL p 使用进近定位点 B ，$b^p = 0$ 否则；$a^p + b^p = 1$ 。此外，决策变量 Δt_e^p 和 Δt_l^p 描述 eVTOL p 在进近定位点 $i, i \in \{A, B\}$ 到达 $ETA^p(i)$ 之前和之后的时间。由于选择到达路线 $\Delta t_{l,i}^p, i \in \{A, B\}$ 产生的延误，是通过方程 (11) 和 (12) 计算的，其中 T_t^p 是飞行在进近定位点和机场之间的转移时间。

Objective function

目标函数

$$\min \sum_{p \in G} c_e^p \cdot \Delta t_e^p + c_l^p \cdot \left(\Delta t_l^p + a^p \cdot \Delta t_{l,A}^p + b^p \cdot \Delta t_{l,B}^p \right)$$

(10)

$$\Delta t_{l,A}^p = \max\left(0, \left(ETA^p(A) + T_t^p(A) - ETA^p(B) - T_t^p(B)\right)\right)$$

(11)

$$\Delta t_{l,B}^p = \max\left(0, \left(ETA^p(B) + T_t^p(B) - ETA^p(A) - T_t^p(A)\right)\right)$$

(12)

Equation (13) and (14) define $s^{pq} = 1$ if eVTOL p arrives prior to eVTOL q and $s^{pq} = 0$ otherwise; $z^{pq} = 1$ if eVTOL p and q fly through the same approach fix and $z^{pq} = 0$ otherwise. Constraint (15) ensures that either eVTOL p follows eVTOL q or eVTOL q follows eVTOL p . Constraint (19) ensures that one eVTOL uses only one approach fix. The time window available for landing at the vertiport is described in (16). The earliest possible time of arrival RTA_e^p is derived from the flight performance model (see Section III-B), while the latest RTA_l^p results from the battery model (see Section III-C). Similarly, the earliest and latest possible time of arrival at approach fix A and B are given in equations (17) and (18), respectively. Equation (20) ensures that if eVTOL p and q go through the same approach fix, the reverse is also true. Equations (21) and (22) further define $z^{pq} = 1$ to if both eVTOL p and q use approach fix A and B, respectively. Equations (23) and (24) define $z^{pq} = 0$ if eVTOLs p and q fly through different approach fixes. Equations (25-27) ensure a time-based separation of at least Δt_{sep}^{qp} if p

follows q at the vertiport and the approach fixes. Lastly, equations (28-31) show the calculation for the Big-M method and define the RTA for eVTOL p using approach fix A and B, respectively. Constraints

方程 (13) 和 (14) 定义了 $s^{pq} = 1$ 如果 eVTOL p 比 eVTOL q 先到达以及 $s^{pq} = 0$ 反之； $z^{pq} = 1$ 如果 eVTOL p 和 q 飞越相同的进近定位点以及 $z^{pq} = 0$ 反之。约束 (15) 确保 eVTOL p 要么跟随 eVTOL q ，要么 eVTOL q 跟随 eVTOL p 。约束 (19) 确保每个 eVTOL 只使用一个进近定位点。在垂直机场可用的着陆时间窗口在 (16) 中描述。最早可能的到达时间 RTA_e^p 是从飞行性能模型 (参见第 III-B 节) 得出的，而最晚时间 RTA_l^p 则来自电池模型 (参见第 III-C 节)。同样，到达进近定位点 A 和 B 的最早和最晚可能时间分别在方程 (17) 和 (18) 中给出。方程 (20) 确保如果 eVTOL p 和 q 通过相同的进近定位点，反之亦然。方程 (21) 和 (22) 进一步定义了 $z^{pq} = 1$ 如果两个 eVTOL p 和 q 分别使用进近定位点 A 和 B。方程 (23) 和 (24) 定义了 $z^{pq} = 0$ 如果 eVTOL p 和 q 飞越不同的进近定位点。方程 (25-27) 确保在 eVTOL p 跟随 q 到达垂直机场和进近定位点时至少有 Δt_{sep}^{qp} 的时间间隔。最后，方程 (28-31) 展示了大 M 方法的计算，并分别定义了使用进近定位点 A 和 B 的 eVTOL p 的 RTA。约束

$$s^{pq}, z^{pq}, a^p, b^p = \{0,1\} \ \forall p, q \in G \tag{13}$$

$$\Delta t_e^p, \Delta t_l^p \geq 0 \ \forall p, q \in G \tag{14}$$

$$s^{pq} + s^{qp} = 1 \ \forall p, q \in G \tag{15}$$

$$RTA_e^p \leq RTA^p \leq RTA_l^p \ \forall p \in G \tag{16}$$

$$RTA_e^p (A) \leq RTA^p (A) \leq RTA_l^p (A) \ \forall p \in G \ (17) \tag{17}$$

$$RTA_e^p (B) \leq RTA^p (B) \leq RTA_l^p (B) \ \forall p \in G \ (18) \tag{18}$$

$$a^p + b^p = 1 \ \forall p \in G \ (19) \tag{19}$$

$$z^{pq} = z^{qp} \ \forall p, q \in G \ (20) \tag{20}$$

$$z^{pq} \geq a^p + a^q - 1 \ \forall p, q \in G, p \neq q \ (21) \tag{21}$$

$$z^{pq} \geq b^p + b^q - 1 \ \forall p, q \in G, p \neq q \tag{22}$$

$$z^{pq} \leq \frac{1}{2}a^p - \frac{1}{2}a^q + 1 \ \forall p, q \in G, p \neq q \tag{23}$$

$$z^{pq} \leq \frac{1}{2}b^p - \frac{1}{2}b^q + 1 \ \forall p, q \in G, p \neq q \tag{24}$$

$$RTA^p \geq RTA^q + \Delta t_{sep}^{qp} - M^{pq} \cdot s^{pq} \tag{25}$$

$$RTA^p (A) \geq RTA^q (A) + \Delta t_{sep}^{qp} \cdot z^{qp} - M^{pq} \cdot s^{pq} \tag{26}$$

$$RTA^p (B) \geq RTA^q (B) + \Delta t_{sep}^{qp} \cdot z^{qp} - M^{pq} \cdot s^{pq} \tag{27}$$

$$\forall p, q \in G, p \neq q$$

$$M^{pq} = RTA_l^q + \Delta t_{sep}^{qp} - RTA_e^p \tag{28}$$

$$RTA^p = a^p \cdot (ETA^p (A) + T_t^p (A)) +$$

$$b^p \cdot (ETA^p (B) + T_t^p (B)) + \Delta t_l^p - \Delta t_e^p \tag{29}$$

$$RTA^p(A) = ETA^p(A) + \Delta t_l^p - \Delta t_e^p \tag{30}$$

$$RTA^p(B) = ETA^p(B) + \Delta t_l^p - \Delta t_e^p \tag{31}$$

IV. CASE STUDY EHANG 184

IV. 案例研究 EHANG 184

We consider a case study for EHANG 184, a multi-rotor eVTOL designed to transport a single passenger [27]. Fig. 4 shows the results from the first step in the algorithm, the GPOPS-II energy-efficient trajectory optimisation for a trivial selection of RTAs. An RTA= 165 s at the approach fix (AF) is the lowest input to ensure convergence to a solution. The cruise flight phase is performed at 500 m altitude and 27.8 m/s cruise speed. The eVTOL arrival scheduling and sequencing is initiated at 3900 m distance from the vertiport (see Section III-A). Based on the results of this optimisation, the eVTOL control system initiates a shallow descent between 3400 m and 1000 m from the vertiport at a constant $V_x = 5.9$ m/s and variable V_h . After passing the AF, a horizontal flight phase is executed at cruise speed and a vertical flight at 2.9 m/s . Fig. 4 also shows the feasible time window of the scheduling tool. For an RTA at the AF between 165 s and 525 s , the eVTOL is required to arrive at the vertiport between 307 s and 667 s as the flight between the AF and vertiport takes 142 s . A trajectory with RTA= 165 s , which also corresponds to the minimum energy required, is used as a baseline trajectory, while its corresponding ETA is an input for the scheduling tool.

我们考虑了 EHANG 184 的一个案例研究，这是一种设计用于运送单个乘客的多旋翼 eVTOL [27]。图 4 显示了算法第一步的结果，即 GPOPS-II 能量优化轨迹对于 RTAs 的简单选择。在接近修正点 (AF) 处的 RTA= 165 s 是确保收敛到解决方案的最低输入。巡航飞行阶段在海平面以上 500 m 高度和 27.8 m/s 巡航速度下进行。eVTOL 到达调度和排序在距离垂直起降场 3900 m 的位置开始 (参见第 III-A 节)。基于这个优化的结果，eVTOL 控制系统在 3400 m 和 1000 m 之间开始浅降，从垂直起降场以恒定的 $V_x = 5.9$ m/s 和变化的 V_h 进行。通过 AF 后，执行巡航速度下的水平飞行阶段和 2.9 m/s 下的垂直飞行。图 4 还显示了调度工具的可行时间窗口。对于 AF 处 RTA 在 165 s 和 525 s 之间的 eVTOL，要求其在 307 s 和 667 s 之间到达垂直起降场，因为从 AF 到垂直起降场的飞行需要 142 s 时间。轨迹 RTA= 165 s ，这也对应于所需的最小能量，被用作基线轨迹，而其对应的预计到达时间 (ETA) 是调度工具的输入。

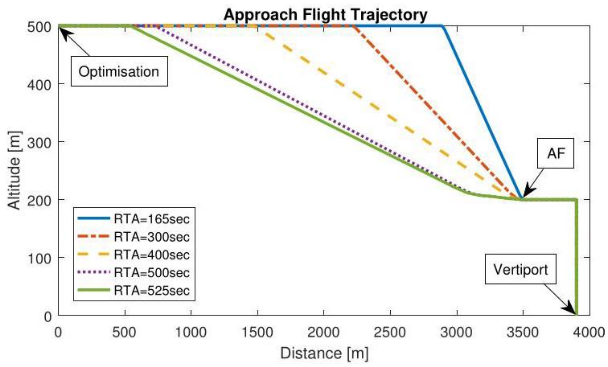

Fig. 4. EHANG 184 energy-optimal trajectory for different RTA to approach fix.

图 4. EHANG 184 在不同 RTA 接近修正点的能量最优轨迹。

The SOC required to perform each of the trajectories shown in Fig. 5 is computed during the second step of the model (see Fig. 3). The battery characteristics specific to EHANG 184 are not made public so it is assumed that Q is 5000Ahr and V_n is 12 V . When the remaining SOC of an incoming eVTOL is equal to e.g. 25% , Fig. 5 indicates RTA = 434 s at the AF, thus an RTA at the vertiport of 576 s can be scheduled at the latest.

执行图 5 所示轨迹所需的 SOC 在模型的第二步计算得出 (见图 3)。EHANG 184 的电池特性并未公开，因此假设 Q 是 5000Ahr 并且 V_n 是 12 V 。当即将到达的 eVTOL 的剩余 SOC 等于例如 25% 时，图 5 表明在 AF 处有 RTA = 434 s ，因此在 576 s 的垂直起降场的 RTA 可以最迟安排。

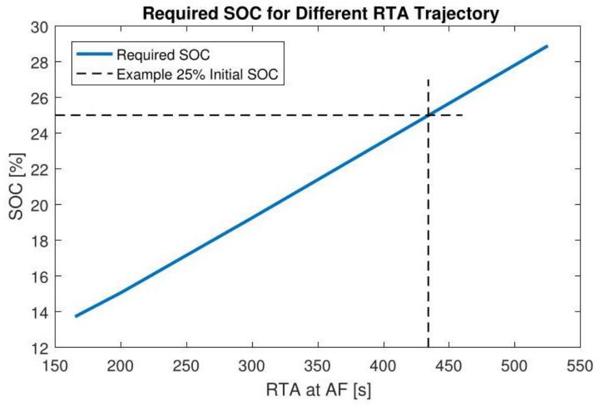

Fig. 5. SOC required to perform different delay absorption trajectories with example 25% SOC and resulting latest RTA of 434 s .

图 5。执行不同延迟吸收轨迹所需的 SOC，以及示例 25% SOC 和得出的最迟 RTA 434 s 。

The eVTOL sequence and schedule are now obtained using the model in step 3 (see Fig. 3). An example of input for our model is shown in Table I. We also assume $c_e = 10$ and $c_l = 30$ [11]. The values for Δt_l^p represent the delay to be absorbed by flying shallow descent, while $\Delta t_{l,AF}^p$ is the delay due to flying through the furthest approach fix (AF). Table II shows that the eVTOLs are rescheduled and sequenced when this minimises delay or when an eVTOL has a low SOC (see eVTOL 8 and 9). Furthermore, eVTOLs are delayed if the separation requirements are not satisfied (see eVTOL 8 and 10). It also selects the AF, which is a means to separate eVTOLs and absorb delay (see eVTOLs 3 and 4).

现在使用步骤 3 中的模型 (见图 3) 获得 eVTOL 的序列和计划。我们模型的输入示例显示在表 I 中。我们还假设 $c_e = 10$ 和 $c_l = 30$ [11]。Δt_l^p 的值代表通过浅降飞行吸收的延迟，而 $\Delta t_{l,AF}^p$ 是由于飞越最远进近定位点 (AF) 而产生的延迟。表 II 显示，当这最小化延迟或当 eVTOL 的 SOC 较低时 (见图 eVTOL 8 和 9)，eVTOLs 会被重新安排和排序。此外，如果不能满足分离要求，eVTOLs 会被延迟 (见图 eVTOL 8 和 10)。它还选择了 AF，这是分离 eVTOLs 和吸收延迟的一种手段 (见图 eVTOLs 3 和 4)。

TABLE I

TEST DATASET OF 10 EHANG 184 EVTOLS

10 架 EHANG 184 eVTOL 的测试数据集

Flight Nr [-]	ETA (A) [s]	ETA (B) [s]	Initial SOC [%]
1	165	180	13
2	250	250	18
3	335	325	25
4	420	410	30
5	505	505	18
6	590	590	13
7	665	675	25
8	750	760	25
9	855	845	14
10	930	930	28

航班号 [-]	预计到达时间 (A) [s]	预计到达时间 (B) [s]	初始 SOC [%]
1	165	180	13
2	250	250	18
3	335	325	25
4	420	410	30
5	505	505	18
6	590	590	13
7	665	675	25
8	750	760	25
9	855	845	14
10	930	930	28

TABLE II

ARRIVAL SEQUENCE AND SCHEDULE FOR TEST DATASET
测试数据集的到达序列和计划

Flight Nr [-]	RTA [s]	Δt_l^p [s]	AF [-]	$\Delta t_{l,AF}^p$ [s]
1	307	0	A	0
2	397	5	B	0
3	487	20	A	10
4	577	25	A	10
5	667	20	A	0
6	757	25	A	0
7	847	40	A	0
9	987	0	B	0
8	1077	185	A	0
10	1167	95	B	0

航班号 [-]	RTA [s]	Δt_l^p [s]	AF [-]	$\Delta t_{l,AF}^p$ [s]
1	307	0	A	0
2	397	5	B	0
3	487	20	A	10
4	577	25	A	10
5	667	20	A	0
6	757	25	A	0
7	847	40	A	0
9	987	0	B	0
8	1077	185	A	0
10	1167	95	B	0

The computational time required to obtain the described results is 2 seconds, using CPLEX LP Solver [34] extension of MATLAB [31] on a computer with Intel CORE i7 processor. To analyse the computational performance of our model, we further vary the number of arriving eVTOLs. We generate ETAs for the eVTOLs using a Poisson process with rate 40 arrivals/hr, while a normal distribution with mean 30% and variance of 5% is used to for the initial SOC. The computational performance is given in Table III. Our model can optimally schedule up to 40 incoming eVTOLs within 79 s , which provides enough time for eVTOLs to absorb the scheduled delay flying energy-efficient shallow descent trajectories through the selected approach fix. However, for a larger number of eVTOL arrivals, further developments of more computational efficient scheduling algorithm are needed.

获取所描述结果所需的计算时间为 2 秒，使用安装在具有 Intel CORE i7 处理器的计算机上的 MATLAB [31] 的 CPLEX LP Solver [34] 扩展。为了分析我们模型的计算性能，我们进一步改变了到达的 eVTOL 数量。我们使用泊松过程以 40 架次/小时的速率生成 eVTOL 的预计到达时间 (ETAs)，同时使用均值为 30% 、方差为 5% 的正态分布来设定初始 SOC。计算性能在表 III 中给出。我们的模型可以在 79 s 内优化安排多达 40 架次到达的 eVTOL，这为 eVTOL 提供了足够的时间通过选定的方法修正飞行节能浅降轨迹来吸收计划的延迟。然而，对于更大数量的 eVTOL 到达，需要进一步开发更高效的计算调度算法。

TABLE III
COMPUTATIONAL TIME FOR DIFFERENT NUMBERS OF ARRIVING
不同到达数量的计算时间 EVTOLS

Number of eVTOLs [-]	10	20	30	40	60	80
Computational time [s]	1.6	9.7	31	79	470	5333

eVTOL 数量 [-]	10	20	30	40	60	80
计算时间 [秒]	1.6	9.7	31	79	470	5333

V. CONCLUSION AND RECOMMENDATIONS

V. 结论与建议

A sequencing and scheduling algorithm with a route selection function for on-demand UAM arrivals is proposed in this paper. The problem is formulated as a mixed integer linear program whose objective is to minimise the total arrival delay. The problem formulation includes constraints such as minimum time separation, eVTOL battery energy and vehicle dynamics. We compute the optimal required times of arrival (RTAs) for eVTOLs arriving at a vertiport within a given planning horizon. Numerical experiments show that our proposed algorithm has near real-time computational performance when scheduling the arrival of up to 40 eVTOLs. Our proposed algorithm and ConOps for terminal airspace design provide a potential solution framework to support safe and efficient on-demand arrivals in Urban Air Mobility (UAM).

本文提出了一个针对按需城市空中出行 (UAM) 到达的排序和调度算法，以及一个路径选择功能。该问题被构建为一个混合整数线性规划问题，目标是最小化总到达延迟。问题构建包括了诸如最小时间间隔、eVTOL 电池能量和车辆动力学等约束。我们计算了在给定规划范围内到达机场的 eVTOL 所需的最优到达时间 (RTAs)。数值实验表明，我们的算法在调度多达 40 架次 eVTOL 到达时具有接近实时的计算性能。我们提出的算法和终端空域设计的概念操作程序 (ConOps) 提供了一个潜在的解决方案框架，以支持城市空中出行 (UAM) 中安全高效的按需到达。

The contribution of this paper is two-fold. Firstly, we propose a ConOps for vertiport airspace design and configuration. We introduce multiple arrival routes with multiple arrival metering fixes. Secondly, this is the first research work on eVTOL arrival sequencing and scheduling for on-demand Urban Air Mobility. The algorithm has arrival route selection capability. It includes a battery discharge prediction model that makes this arrival scheduling algorithm specially designed for eVTOL operations. It outputs landing time slots (or RTAs) for all arriving eVTOLs for minimum total delay. This algorithm can be used as a baseline for future research on optimal UAM arrival scheduling.

本文的贡献有两方面。首先，我们为垂直机场空域设计和配置提出了一个概念操作 (ConOps)。我们引入了多条到达路线和多个到达计量修正点。其次，这是首次对按需城市空中出行 (Urban Air Mobility, UAM) 的电动垂直起降 (eVTOL) 飞机到达排序和调度进行研究。该算法具有到达路线选择功能。它包括一个电池放电预测模型，使得这个到达调度算法特别适用于 eVTOL 飞机的运行。它为所有到达的 eVTOL 飞机输出着陆时间槽 (或 RTAs)，以实现总延迟最小化。该算法可作为未来研究最优 UAM 到达调度的基线。

Future work includes a more in-depth research on the airspace design, both for arrival and departure procedures, as well as safe separation from other aviation traffic in the integrated airspace. Detailed battery testing and modelling are recommended to provide a more accurate model for battery discharge prediction. More efficient optimisation algorithms should be investigated to improve the computational performance of the sequencing and scheduling model. Finally, this arrival sequencing and scheduling algorithm should be incorporated with departure scheduling and conflict detection and resolution models to reach the highest efficiency in Urban Air Mobility and ensure safe flight operations.

后续工作包括对空域设计进行更深入的研究，既包括到达和出发程序，也包括与其他航空交通在集成空域中的安全间隔。建议进行详细的电池测试和建模，以提供一个更准确的电池放电预测模型。应研究更高效的优化算法，以提高排序和调度模型的计算性能。最后，这个到达排序和调度算法应与出发调度和冲突检测与解决模型相结合，以达到城市空中出行的最高效率并确保安全飞行操作。

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