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Abstract-Airport is both the starting and ending point of air traffic. The sharp increase in air traffic flow causes directly traffic congestion in Terminal Maneuvering Area (TMA) which affects the normal operation of the flights. Optimizing departure and arrival procedures is therefore crucial to regulate air traffic flow. This research focuses on generating 3D Standard Instrument Departure routes and Standard Terminal Arrival Routes in TMA at a strategic level. We propose an optimization approach to generate 3D routes avoiding obstacles and assuring a minimum separation between routes. The method combines Fast Marching Method and Simulated Annealing.

摘要-机场是航空交通的起点和终点。航空交通流的急剧增加直接导致终端机动区 (TMA) 的交通拥堵，这影响了航班的正常运行。因此，优化起飞和降落程序对于调节航空交通流至关重要。本研究着重于在战略层面生成 TMA 中的三维标准仪表离场路线和标准终端进近路线。我们提出了一种优化方法来生成避开障碍物并确保路线之间最小间隔的三维路线。该方法结合了快速行进法和模拟退火。

Keywords-TMA; SID; STAR; Optimization; Fast Marching Method; Simulated Annealing

关键词-TMA；SID；STAR；优化；快速行进法；模拟退火

I. INTRODUCTION

I. 引言

Nowadays air transport in Europe and North America has basically reached saturation. The sharp increase in air traffic flow causes directly traffic congestion in Terminal Maneuvering Area (TMA), which affects the normal operation of the flights. TMA is designed to handle aircraft arriving to and departing from airports and perhaps is one of the most complex types of airspace.

如今，欧洲和北美的航空运输基本上已经达到饱和。航空交通流的急剧增加直接导致终端机动区 (TMA) 的交通拥堵，这影响了航班的正常运行。TMA 旨在处理抵达机场和从机场起飞的飞机，可能是最复杂的空域类型之一。

Currently, the Standard Instrument Departure (SID) and Standard Terminal Arrival Route (STAR) are designed manually based on the airport layout, existing Navaid infrastructures and nearby constraints [1]. Therefore automatically designing departure and arrival routes at a strategic level in 3D is interesting as it may help to regulate air traffic flow.

目前，标准仪表离场 (SID) 和标准终端进近路线 (STAR) 是基于机场布局、现有的导航基础设施和附近的限制手动设计的 [1]。因此，在战略层面自动设计三维的起飞和降落路线是很有意义的，因为它可能有助于调节航空交通流。

Planning optimal aircraft routes is a rich and dynamic research area in Air Traffic Management (ATM). Routes design in TMA is however a specific problem for which to our knowledge there is not a rich literature. In [1] and [2], two problems closed to the one considered in the present paper are studied. In [1], for a given weather forecast, the author develops an integer programming approach to optimally choose terminal area arrival and departure fixes as well as sector boundaries. In [2], an optimization algorithm is proposed for aircraft routings that minimizes the noise impact in the residential communities surrounding the airport. The aim of this study is to give an optimization approach to automatically design 3D departure and arrival routes at a

规划最优航线是空中交通管理 (ATM) 领域一个丰富且动态的研究领域。然而，在终端机动区 (TMA) 中的航线设计是一个特定的问题，据我们所知，相关文献并不丰富。在文献 [1] 和 [2] 中，研究了两个与本文考虑的问题相近的问题。在 [1] 中，作者针对给定的天气预报，开发了一种整数规划方法，以最优选择终端区域的到达和出发定位点以及扇区边界。在 [2] 中，提出了一种优化算法，用于飞机航线规划，以最小化机场周边居民社区的噪音影响。本研究的目标是给出一种优化方法，用于在战略层面自动设计三维的出发和到达航线，同时考虑一些运营约束。

strategic level taking into account some operational constraints.

在考虑一些运营约束的情况下，进行战略层面的三维出发和到达航线自动设计。

This paper is organized as follows: Section II describes the problem and introduces the TMA model; Section III presents the proposed approach to solve the problem. Section IV gives some preliminary simulation results. Finally, Section V gives conclusions and future directions.

本文的组织结构如下: 第二节描述问题并介绍 TMA 模型；第三节呈现了解决问题的方法；第四节给出了一些初步的仿真结果。最后，第五节给出结论和未来的研究方向。

II. PROBLEM DESCRIPTION AND MODELIZATION

第二节问题描述与建模

A. Problem Description

A. 问题描述

TMA is a designated area of controlled airspace surrounding one or several airports. It is designed to handle aircraft arriving to and departing from airports. It is one of the most complex types of airspace.

TMA 是围绕一个或多个机场的指定管制空域。它旨在处理抵达和离开机场的飞机。这是最复杂的空域类型之一。

The SID is a flight route followed by aircraft after takeoff from an airport. The STAR is a route which connects the last enroute way-point to the Initial Approach Fix. These routes are specified by a sequence of waypoints. Each aircraft flying under Instrument Flight Rules (IFR) through the TMA must follow a SID when departing an airport, and a STAR when arriving. The design of SIDs and STARs has to take into account operational and environmental constraints, such as vertical and horizontal flow separation, noise restrictions, etc.

SID 是飞机起飞后从机场遵循的飞行路线。STAR 是连接最后一个航路点与初始进近定位点的路线。这些路线由一系列航点指定。每架在 TMA 下按照仪表飞行规则 (IFR) 飞行的飞机在离开机场时必须遵循 SID，在到达时必须遵循 STAR。SID 和 STAR 的设计必须考虑运营和环境约束，如垂直和水平流量分离、噪音限制等。

In the following, we propose a method to design automatically the SIDs and STARs for a given TMA configuration, characterized by a number of entry/exit points at the boundary of TMA, arrival/departure points around the runways, forbidden areas and some operational constraints.

在以下内容中，我们提出了一种方法，用于自动为给定的 TMA 配置设计 SID 和 STAR，该配置的特点是 TMA 边界的入口/出口点数量、跑道周围的到达/出发点、禁飞区和一些运营限制。

B. Modelization

B. 建模

In this study, we only consider TMA surrounding one airport. The number and configuration of runways are known. We suppose that the runways have the sufficient distances and equipments for landing and taking off for all types of aircraft. Let N be the total amount of flights arriving at and departing from the airport. As TMA is generally designed in a circular configuration centered on the geographic coordinates of the airport, we assume it is composed of two concentric circles C_1 and C_2 , with radius R_1 and R_2 respectively. Aircraft enter into or exit from TMA on several points located on C_1 . More precisely, let $\mathbb{O}=\{O_1,\ldots,O_{n_{in}},O_{n_{in}+1},\ldots,O_{n_{in}+n_{out}}\}$ be the set of entry and exit points, where the first n_{in} points are the entry points and the remaining $n_{\text{ out }}$ ones are exit points.

在本研究中，我们仅考虑围绕一个机场的 TMA。跑道的数量和配置是已知的。我们假设跑道具有足够的距离和设备，以满足所有类型飞机的起降需求。设 N 为到达和离开机场的总航班量。由于 TMA 通常以机场地理坐标为中心的圆形配置设计，我们假设它由两个同心圆 C_1 和 C_2 组成，半径分别为 R_1 和 R_2 。飞机在 C_1 上的几个点进入或离开 TMA。更准确地说，设 $\mathbb{O}=\{O_1,\ldots,O_{n_{in}},O_{n_{in}+1},\ldots,O_{n_{in}+n_{out}}\}$ 为入口和出口点的集合，其中前 n_{in} 个点是入口点，其余的 $n_{\text{ out }}$ 点是出口点。

Similarly, aircraft arrive to or departure from airport through several points located on C_2 . Suppose that $\mathbb{I}=\left\{I_1,\ldots,I_{n_{arr}},I_{n_{arr}+1},\ldots,I_{n_{arr}+n_{dep}}\right\}$ is the set of arrival and departure points, where the first n_{arr} points are the arrival points and the remaining $n_{\text{ dep }}$ ones are departure points. An example of TMA is shown in Fig. 1 with $\mathbb{O}=\{O_1,O_2,O_3,O_4\}$ and $\mathbb{I}=\{I_1,I_2\}$.

同样，飞机通过 C_2 上的几个点到达或离开机场。假设 $\mathbb{I}=\left\{I_1,\ldots,I_{n_{arr}},I_{n_{arr}+1},\ldots,I_{n_{arr}+n_{dep}}\right\}$ 是到达和出发点的集合，其中前 n_{arr} 个点是到达点，其余的 $n_{\text{ dep }}$ 点是出发点。TMA 的一个示例在图 1 中展示，其中包含 $\mathbb{O}=\{O_1,O_2,O_3,O_4\}$ 和 $\mathbb{I}=\{I_1,I_2\}$ 。

The routes that we want to design connect some points on C_1 to some other points on C_2 . Let $\mathbb{K}\subset\mathbb{O}\times\mathbb{I}$ be the subset which contains the pairs of points to be connected on C_1 and C_2 . Furthermore, we suppose that the proportion of flights on each route is given.

我们希望设计的航线将 C_1 上的某些点连接到 C_2 上的其他点。设 $\mathbb{K}\subset\mathbb{O}\times\mathbb{I}$ 为包含要在 C_1 和 C_2 上连接的点对的子集。此外，我们假设每条航线上的航班比例是给定的。

The design of SIDs and STARs can be done in an optimal way, with respect to a given criterion, such as minimizing the total distance flown by all flights. Therefore, the problem can be expressed as an optimization problem. In the following, we give the main elements of our optimization model.

SID 和 STAR 的设计可以根据给定的标准以最优方式进行，例如最小化所有航班飞行的总距离。因此，该问题可以表述为一个优化问题。下面，我们给出了优化模型的主要元素。

Given $(i, j) \in \mathbb{K}$, a route connecting points O_i and I_j can be defined as a function:

给定 $(i, j) \in \mathbb{K}$ ，可以定义一个连接点 O_i 和 I_j 的路由作为函数:

$$\gamma_{ij} : [0; 1] \rightarrow \mathbb{R}^3 \tag{1}$$

where $\gamma_{ij}(0)$ represents the starting point and $\gamma_{ij}(1)$ is the ending point. There are two possible cases: route γ_{ij} either starts from an entry point on C_1 and ends at an arrival point on C_2 ; or it starts from a departing point on C_2 and ends at an exit point on C_1 . This can be expressed by the following equations:

其中 $\gamma_{ij}(0)$ 表示起点，$\gamma_{ij}(1)$ 是终点。有两种可能的情况: 路由 γ_{ij} 要么从 C_1 上的一个入口点开始，在 C_2 上的一个到达点结束；要么从 C_2 上的一个出发点开始，在 C_1 上的一个出口点结束。这可以通过以下方程表示:

$$\left.\begin{array}{l}\gamma_{ij}(0) = O_i \\ \gamma_{ij}(1) = I_j\end{array}\right\} \text{ if } 1 \leq i \leq n_{in} \text{ and } 1 \leq j \leq n_{arr} \tag{2}$$

$$\left.\begin{array}{l}\gamma_{ij}(0) = I_i \\ \gamma_{ij}(1) = O_j\end{array}\right\} \text{ if } n_{arr} + 1 \leq i \leq n_{arr} + n_{dep}$$

$$\text{and } n_{\text{ in }} + 1 \leq j \leq n_{\text{ in }} + n_{\text{ out }} . \tag{3}$$

We denote the components of γ_{ij} in axis(x, y, z)by $(\gamma_{ijx}, \gamma_{ijy}, \gamma_{ijz})$ respectively.

我们用 γ_{ij} 在轴 (x, y, z) 上的分量分别表示为 $(\gamma_{ijx}, \gamma_{ijy}, \gamma_{ijz})$ 。

In this study, we consider two main constraints: the forbidden areas and the minimum separation. In TMA some special areas exist, where an aircraft is not allowed to fly, for instance geographical obstacles, big cities, military areas, etc. We refer to these areas as ”forbidden areas”. Furthermore, in air traffic control, aircraft have to be maintained at a minimum separation distance to reduce the risk of collision. The minimum vertical separation is 1000ft in TMA for all aircraft. Generally, the minimum horizontal separation in TMA is equal to 3NM . We consider this separation equal to 6NM , in order to take into account the deviation of aircraft from the pre-designed route. The aircraft protection zone is shown in Fig. 2.

在本研究中，我们考虑两个主要约束: 禁飞区和最小间隔。在 TMA 中存在一些特殊区域，飞机不允许飞行，例如地理障碍、大城市、军事区域等。我们称这些区域为“禁飞区”。此外，在空中交通管制中，飞机必须保持最小间隔距离以减少碰撞风险。TMA 中所有飞机的最小垂直间隔是 1000ft 。通常，TMA 中的最小水平间隔等于 3NM 。我们考虑这个间隔等于 6NM ，以便考虑到飞机从预先设计的路由上的偏移。飞机保护区如图 2 所示。

The separation constraints are expressed as follows,

分离约束表达如下，$\forall (i, j), (k, l) \in \mathbb{K}$, $\forall (\mu_1, \mu_2) \in [0; 1]$

$$\sqrt{\left(\gamma_{ijx}(\mu_1) - \gamma_{klx}(\mu_2)\right)^2 + \left(\gamma_{ijy}(\mu_1) - \gamma_{kly}(\mu_2)\right)^2} \geq 6\text{NM}$$

(4)

$$\left|\gamma_{ijz}(\mu_1) - \gamma_{klz}(\mu_2)\right| \geq 1000\text{ft}. \tag{5}$$

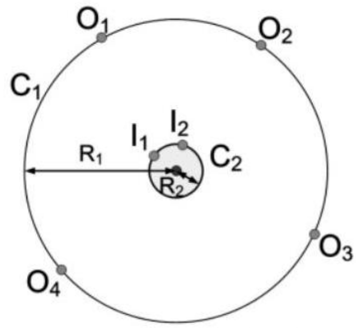

Figure 1. Example of TMA

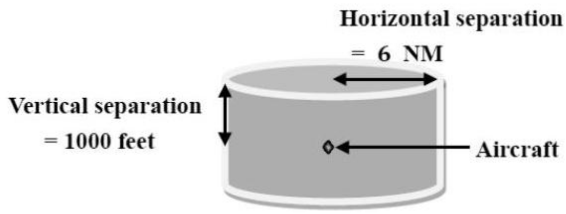

Figure 2: Aircraft protection zone cylinder in 3D
图 2: 3D 中的飞机保护区圆柱
We minimize the total distance flown by all the flights during a certain period.
我们最小化在特定时期内所有航班飞行的总距离。

$$L = \sum_{(i,j)\in\mathbb{K}} w_{ij} N l_{ij} \tag{6}$$

where l_{ij} is the length of route γ_{ij} and w_{ij} is the proportion of flights on route γ_{ij} .
其中 l_{ij} 是路线 γ_{ij} 的长度，w_{ij} 是在路线 γ_{ij} 上的航班比例。

III. SOLUTION APPROACHES

III. 解决方案方法

To deal with the difficulty of the problem, we propose a three-steps solution approach.
为了解决这个问题的难度，我们提出了一个三步骤的解决方案方法。
a. Compute an individual route by Fast Marching Method (FMM) and Gradient Descent method, where we take into consideration the forbidden areas.
a. 通过快速行进法 (FMM) 和梯度下降法计算单个路线，其中我们考虑了禁飞区。
b. Given a fixed order of the routes, compute sequentially the routes taking into account the minimum separation constraints.
b. 给定路线的固定顺序，依次计算路线，同时考虑最小间隔约束。
c. Find an order minimizing (6) by applying Simulated Annealing (SA).
c. 通过应用模拟退火 (SA) 找到一个使 (6) 最小化的顺序。

A. Designing one route

A. 设计一条路线

Given $(i,j)\in\mathbb{K}$, we first compute a route yielding the minimal travel time from $\gamma_{ij}(0)$ to $\gamma_{ij}(1)$, see (2) and (3). The minimal-time optimal trajectory problem corresponds to a wave front propagation problem [3], [4]. In the isotropic case where the wave propagation speed does not depend on the direction, the equation that describes the evolution of the front is in the following form, known as the Eikonal equation:
给定 $(i,j)\in\mathbb{K}$ ，我们首先计算一条从 $\gamma_{ij}(0)$ 到 $\gamma_{ij}(1)$ 的最短旅行时间的路线，参见 (2) 和 (3)。最小时间最优轨迹问题对应于波前传播问题 [3]、[4]。在波传播速度不依赖于方向的同质情况下，描述波前演化的方程是以下形式，即著名的 Eikonal 方程:

$$\| \nabla u(x) \| F(x) = 1 \tag{7}$$

supplemented by the boundary condition

辅以边界条件

$$u(\gamma_{ij}(0)) = 0 \tag{8}$$

where x is the front position (corresponding to the aircraft position); $u(x)$ represents the time at which the front reaches the point x and $F(x)$ is the speed at the point x . In order to take into account the constraints, we associate a different propagation speed to points belonging to forbidden areas and to points located elsewhere, by expressing the speed at point x as follows:

其中 x 是波前位置 (对应于飞机位置)；$u(x)$ 表示波前到达点 x 的时间，$F(x)$ 是点 x 的速度。为了考虑这些约束，我们将不同的传播速度与属于禁飞区的点和位于其他位置的点关联起来，通过以下方式表达点 x 的速度:

$$F(x) = (1 - \alpha(x)) \cdot F \tag{9}$$

with $\alpha(x) \in [0;1)$ and F a constant value. In strictly forbidden area we consider $\alpha(x) = 0.99$ and elsewhere $\alpha(x) = 0$.

其中 $\alpha(x) \in [0;1)$ 和 F 是常数值。在严格禁飞区我们考虑 $\alpha(x) = 0.99$ ，在其他地方考虑 $\alpha(x) = 0$ 。

To solve the wave front propagation problem in the isotropic case, we apply the FMM developed by Sethian in [5]. The general idea of FMM is that the front propagates towards the points that it reaches at a minimum time. At the end of the evolution, we get the minimum time to reach any point in space starting from $\gamma_{ij}(0)$. Then the Gradient Descent method is used to generate the route. It starts from the ending point $\gamma_{ij}(1)$ and moves towards the starting point $\gamma_{ij}(0)$ by taking steps proportional to the opposite of the gradient of $u(x)$ at the current point x .

为了解决各向同性情况下的波前传播问题，我们应用了 Sethian 在 [5] 中发展的快速多级方法 (FMM)。FMM 的基本思想是波前向它最早到达的点传播。在演化结束时，我们得到从 $\gamma_{ij}(0)$ 出发到达空间中任意点的最短时间。然后使用梯度下降法生成路径。它从终点 $\gamma_{ij}(1)$ 开始，通过采取与当前点 x 处 $u(x)$ 梯度的相反方向成比例的步骤向起点 $\gamma_{ij}(0)$ 移动。

B. Generating all routes

B. 生成所有路径

Given an order of the routes, we compute sequentially routes as explained in the first step. In order to satisfy the minimum separation constraints, once a route is computed, this route and its protection zone are considered as additional forbidden area constraints for the remaining routes.

给定路径的顺序，我们按照第一步解释的方法依次计算路径。为了满足最小间隔约束，一旦计算出一个路径，这个路径及其保护区将被视为剩余路径的额外禁行区域约束。

C. Getting an optimal order

C. 获取最优顺序

By changing the order of routes, the length of each route is modified, because the routes computed previously have an influence on the shapes of the following routes. The number of possible choices for route order is $k!$, where $k = \mathrm{card}(\mathbb{K})$, that can be rapidly increase with k . To get an optimal order, we apply a Simulated Annealing that is a stochastic global optimization method. It is conveniently applied to large scale problems.

通过改变路径的顺序，可以修改每条路径的长度，因为先前计算的路径会影响后续路径的形状。路径顺序的可能选择数量为 $k!$ ，其中 $k = \mathrm{card}(\mathbb{K})$ ，这可能会随着 k 迅速增加。为了获得最优顺序，我们应用了模拟退火算法，这是一种随机全局优化方法。它适用于大规模问题。

Simulated Annealing works by emulating the physical process whereby a solid is slowly cooled so that when eventually its structure is ”frozen”, a minimum energy configuration is obtained. For our application, the state space is the permutation group of the k routes and a solution is an element of this group, representing a selected order of routes. The algorithm starts with a random solution, then at each iteration a new solution is generated by selecting randomly two positions in the previous solution and inversing the order of the sub sequencing between them.

模拟退火算法通过模拟固体缓慢冷却的物理过程工作，当其结构最终“冻结”时，获得最小能量配置。对于我们的应用，状态空间是 k 条路径的排列群，一个解是这个群的一个元素，代表一个选定的路径顺序。算法从一个随机解开始，然后在每次迭代中通过在先前解中随机选择两个位置并反转它们之间的子序列顺序来生成一个新的解。

IV. SIMULATION RESULTS

IV. 仿真结果

In this section we present the results obtained at each step A, B, C in Section III.

在本节中，我们展示了在第三部分每个步骤 A, B, C 获得的结果。

We work with an airport with two parallel runways A and B . Their orientations are(12L,30R)and(12R,30L) respectively. The orientation $12L$ of runway A and the orientation $12R$ of runway B are only used for takeoff; the other two sides are only used for landing. The coordinate of the center O of the two circles C_1 and C_2 is ($100 \text{ km}, 100 \text{ km}, 0 \text{ ft}$). Fig. 3 shows this configuration.

我们在一个拥有两条平行跑道的机场工作 A 和 B 。它们的朝向分别是 (12L，30R) 和 (12R，30L)。跑道 A 的朝向 $12L$ 和跑道 B 的朝向 $12R$ 仅用于起飞；另外两边仅用于着陆。两个圆 O 和 C_1 的中心坐标 C_2 是 ($100 \text{ km}, 100 \text{ km}, 0 \text{ ft}$)。图 3 展示了这种配置。

Moreover, $R_1 = 100 \text{ km}$ and $R_2 = 10 \text{ km}$; Entry/exit points are $\{O_1, O_2, O_3, O_4\}$ and $\{O_5, O_6, O_7, O_8\}$ respectively. Arrival/departure points are $\{I_1, I_2\}$ and $\{I_3, I_4\}$ respectively. The z -coordinates of points $O_i, i \in \{1, \ldots, 8\}$ and $I_i, i \in \{1, \ldots, 4\}$ are 25000ft and 4000ft respectively. Their x, y -coordinates are presented in Table.1. The number of flight is $N = 20000$; The pairs to be connected are $\mathbb{K} = \{(O_1, I_1)$,

此外，$R_1 = 100 \text{ km}$ 和 $R_2 = 10 \text{ km}$ ；入口/出口点分别是 $\{O_1, O_2, O_3, O_4\}$ 和 $\{O_5, O_6, O_7, O_8\}$ 。到达/出发点分别是 $\{I_1, I_2\}$ 和 $\{I_3, I_4\}$ 。点 z 和 $O_i, i \in \{1, \ldots, 8\}$ 的 $I_i, i \in$ -坐标 $\{1, \ldots, 4\}$ 分别是 25000ft 和 4000ft 。它们的 x, y -坐标在表 1 中给出。航班的数量是 $N = 20000$ ；需要连接的航班对是 $\mathbb{K} = \{(O_1, I_1), (O_2, I_1), (O_3, I_2), (O_4, I_2), (I_3, O_5), (I_3, O_8), (I_4, O_7), (I_4, O_6)\}$The proportion of flight on each route is $5\%, 20\%, 15\%$, $10\%, 5\%, 15\%, 25\%$ and 5% respectively.

每条航线上的航班比例分别是 $5\%, 20\%, 15\%$ ， $10\%, 5\%, 15\%, 25\%$ 和 5% 。

A. Designing one route

A. 设计一条航线

In this step, we firstly generate a route connecting the pair (O_1, I_1) . Fig. 4 presents the simulation results. Three obstacles are taken into consideration. The area located in the center of an obstacle in dark gray is the surrounding area that can be flown over considering a penalty. The simulation result shows that the generated route is smooth and avoids the forbidden area.

在此步骤中，我们首先生成一条连接航班对 (O_1, I_1) 的航线。图 4 展示了仿真结果。考虑了三个障碍物。障碍物中心位置深灰色区域是考虑惩罚后可以飞越的周边区域。仿真结果显示，生成的航线平滑且避开了禁飞区。

B. Generating all routes

B. 生成所有航线

The simulation result is shown in Fig. 5 where the black routes are the STARs and the gray ones are the SIDs. The obstacles are unchanged.

仿真结果如图 5 所示，其中黑色航线是 STARs，灰色航线是 SIDs。障碍物保持不变。

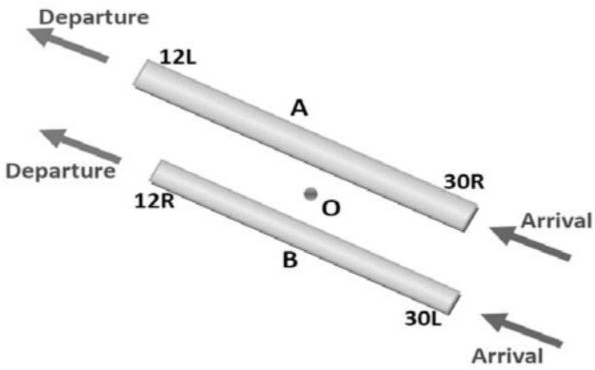

Figure 3: Runway configuration
图 3: 跑道配置
TABLE I. COORDINATES IN AXIS x AND y
表 I. 轴 x 和 y 上的坐标

	$\mathbf{0_1}$	$\mathbf{O_2}$	$\mathbf{O_3}$	$\mathbf{O_4}$	$\mathbf{0_5}$	$\mathbf{O_6}$	$\mathbf{O_7}$	$\mathbf{O_8}$
$\mathbf{x}\,(km)$	100	200	120	0	140	180	40	20
y(km)	200	100	2	100	194	40	20	160

	$\mathbf{0_1}$	$\mathbf{O_2}$	$\mathbf{O_3}$	$\mathbf{O_4}$	$\mathbf{0_5}$	$\mathbf{O_6}$	$\mathbf{O_7}$	$\mathbf{O_8}$
$\mathbf{x}\,(km)$	100	200	120	0	140	180	40	20
y(千米)	200	100	2	100	194	40	20	160

	$\mathbf{I_1}$	$\mathbf{l_2}$	$\mathbf{I_3}$	$\mathbf{I_4}$
x (km)	110	100	100	90
y (km)	100	90	110	100

	$\mathbf{I_1}$	$\mathbf{l_2}$	$\mathbf{I_3}$	$\mathbf{I_4}$
x (km)	110	100	100	90
y (千米)	100	90	110	100

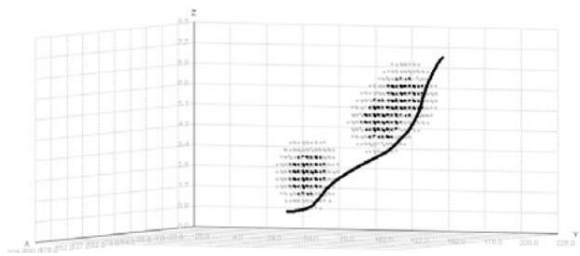

Figure 4: Designing one route (the axes x, y, z have different scales; the range of axes x and y is $[0; 225$ km$]$, the one of axis z is $[0; 8.5$ km$]$)
图 4: 设计一条航线 (坐标轴 x, y, z 的刻度不同；坐标轴 x 和 y 的范围是 $[0; 225$ km$]$ ，坐标轴 z 的范围是 $[0; 8.5$ km$]$)

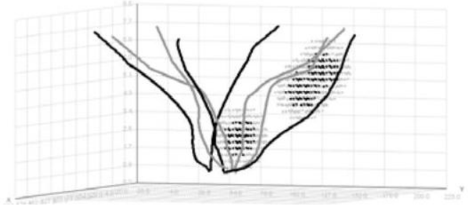

Figure 5: Generating all routes (the axes x, y, z are represented in the same way as in Fig.4)
图 5: 生成所有航线 (坐标轴 x, y, z 的表示方式与图 4 相同)

C. Getting an optimal order

C. 获取最优顺序

The simulation starts from a randomly generated order, with the initial total distance $L_{\text{init}} = 2204141$ km . By applying Simulated Annealing, we find the minimum total distance $L_{\min} = 2008012$ km . The relative reduction $\Delta = (L_{\text{init}} - L_{\min})/L_{\min}$ is equal to 9.7% .

模拟从一个随机生成的顺序开始，初始总距离为 $L_{\text{init}} = 2204141$ km 。通过应用模拟退火，我们找到最小总距离 $L_{\min} = 2008012$ km 。相对减少量 $\Delta = (L_{\text{init}} - L_{\min})/L_{\min}$ 等于 9.7% 。

V. CONCLUSION AND PERSPECTIVES

V. 结论与展望

In this paper, we introduce a methodology to generate automatically SIDs and STARs in TMA at a strategic level, considering forbidden areas and minimum separation constraints.

在本文中，我们介绍了一种在战略层面自动生成 TMA 中的 SID 和 STAR 的方法，考虑了禁飞区和最小间隔限制。

In future work, in order to get closer to the operational context, we plan to consider some other constraints in TMA, for instance the route curvature, noise restrictions, runway capacities, etc. To deal with the more complex problem, the study will focus on mathematical modelization aspects as well as on the development of efficient determinist and stochastic optimization methods. Furthermore, we will address route design at tactical level taking into account weather events. Some routes can be blocked and have to be dynamically redesigned in order to address efficiently the demand.

在未来的工作中，为了更接近操作环境，我们计划考虑 TMA 中的一些其他限制，例如航线的曲率、噪音限制、跑道容量等。为了处理更复杂的问题，研究将聚焦于数学模型化方面以及高效确定性随机优化方法的发展。此外，我们还将研究战术层面的航线设计，考虑天气事件。一些航线可能会被封锁，需要动态重新设计，以有效地应对需求。

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