Significant weather areas mapping for UAV route planning

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Abstract
Unmanned aviation opens unique and promising opportunities for many areas of people's activity, including cargo and goods delivery, monitoring different objects and processes, agriculture, security, photography, and many other fields. All these services are considered fundamental in the frame of the novel concepts, such as IoT, urban air mobility, smart cities, and others. At the same time, there are challenges to safely integrating unmanned aircraft systems (UAS) into the airspace and introducing them into the novel smart ecosystem of the prospective concepts. One of the challenges is to provide regular, safe, ecological services in a highly dynamic environment and under changing weather conditions. In this paper, we propose an algorithm that allows for collecting weather information to identify and map areas inside the urban environment affected by weather conditions significant for UAV flights with increased periodicity. The simulation results demonstrating the benefits of UAS flight safety are presented and discussed. The study results are proposed for use when planning and scheduling flight routes in the urban air mobility concept frame.

Keywords
UAV, Air mobility, urban air mobility, group flight, IoT, weather hazards, UAS flight planning, UAS trajectory correction, air navigation

1. Introduction

The wide use of unmanned aircraft vehicles (UAV) coincides with the society and industry transformation into the interconnected and smart ecosystem that is based on the information exchange and processes automation without evident human support. This interconnected system of physical things or objects is known as Internet of Things (IoT). In this context, the unmanned aviation opens unique and promising opportunities for many areas of people activity including cargo and goods delivery, monitoring of different objects and processes, using in agriculture, security, photography and many other [1,2]. The developing technologies and modern digital solutions consider the use of UAVs as an important player of the Urban Mobility (UM) concept [3, 4], that, in turn, is the component of IoT. In the frame of UM concept, the services delivery organization is partially shifted into the sky. These include the low-level transportation of goods and people, emergency services provision and many other public services [5].

Despite the evident benefits of the UAV application, the challenges to integrate safely the unmanned aircraft systems (UAS) into the airspace and introduce them into the novel smart ecosystem should be considered, analyzed and taken into account. The challenges can be connected with matter of safety and security, privacy, standardization and regulation, technical complexity when application for the IoT purposes, noises and impact on environment, sustainability as well. Also, the restriction connected with operation in highly dynamic environment and under changing conditions should be taken into account as well as questions connected with control and management of group flights and available runways or take-off or landing places [6,7]. Some of the

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challenges connected with flight route planning and in-flight optimization to provide the mission safety and economic feasibility.

2. Motivation

As the weather still is the factor that influences the aviation significantly, it was our motivation to focus on the restrictions connected with weather-related hazards for UAV flights and mission realization. We propose an algorithm that allows to collect weather information for identification of areas inside the urban environment that are affected by weather conditions significant for UAVs flights with increased periodicity. The information can be used when flight route planning and scheduling. The factors that make impact into flight route planning and taken into account are the climate, topography, urban peculiarities (number of buildings, their orientation, dimensions, material of constructions), seasonal weather variation. The UAVs are considered as instruments to collect meteorological data for further processing and selection of optimal flight paths for regular operations.

3. Related works overview

Exploring the ability to integrate the services in the frame of UM concept the study to evaluate their safety is under attention now. Many papers consider now the route optimization in the frame of UAV utilization for novel concepts. In [8] the route planning methods for advanced air mobility (AAM) using 3D GIS environment are considered. In paper [9] the route optimization algorithm on the base of quantum annealing. In paper [10] considers optimization processes taking into account colony algorithm, node transfer rules and information transfer rules. Papers [11] also focuses on route planning for air delivery. Considered papers the attention was paid to the geographical characteristics, urban peculiarities and air intensity when optimization task formulation. The risk-aware to third parties route planning is presented and discussed in [12]. Paper [13] explores the optimization focusing on the next strategies: adjusting traffic light phases and implementing a controlled Y-shaped intersection. Papers [12] also take into account the risks that can be done to people when route planning. Paper [13] focuses on optimizing existing structures considering in detail current situation in Ukraine.

The weather is also the factor that influences the UAS flight safety, regularity and fly ability. The atmospheric characteristics influence the aircraft performances. Significant weather phenomena restrict or even make the flight impossible. In papers [14,15] the analysis of the weather phenomena that influence the UAS operation is done. The unmanned aircraft systems combine the UAV, communication lines, navigation systems, remote pilots, control system. The weather can affect not only the physical part of the UAS, that is UAV, but other components as well. Therefore, one can find studies on influence of the weather on the UAV parameters [16,17], Also there are studies focusing on influence of weather on UAS communication [18]. In paper [19] the UAS faults caused by the weather are studied. In [20] the research on the evaluation of how to integrate air taxi into airspace above urban environment under all kind of weather conditions is presented.

The problem of influence of weather on the route planning was studied for general aviation. The papers [21 -23] considers this problem. Nowadays, the influence of weather on UAS flight and route planning becomes important. Especially important is the weather phenomena that are characterized with high dynamics, are difficult to forecast or predict the exact place or time of formation. Paper [24] consider the colony algorithm for UAV route planning taken into account the weather threat. In paper [25-27] the optimization problem when cargo delivery with UAV is proposed to solve taking into account minimization in energy consumption and time of delivery. To achieve the goal the weather forecast and good time window is taken into account. In paper [28] the approach to predict unfavorable weather conditions for UAV mission planning is considered. The weather as one of the parameters of uncertainty is considered in the approach for

UAV fleet routing in paper [29]. In paper [30] the analysis of weather influence on particular type of UAV and mission peculiarities are analyzed to develop the decision support system and software solution for route planning and correction. The analysis of the latest research shows the importance of the problem to organize the safe, regular and economically efficient UAS missions in the frame of the novel concepts of the industry and community development.

4. UAV as the instrument for service provision and weather

The unique opportunities to use UAVs in the frame of IoT concept is provided by the range of advantages that are not limited presented below:

- UAVs can be easily deployed in the system,
- can serve as a platform for sensors of different kind,
- flexibility and adaptability for different missions and scenarios, operation in the remote areas,
- low-cost and multi-purpose instrument.

The services that can be delivered by UAV include and are not limited with communication network support, surveillance, transportation, delivery. The diversity of the mission provides the difference in approaches to plan the routes and mode of operation of the UAV. For example, in case of communication network support it is important to consider system configuration, iterability with other devices, security-related issues. In case of delivery services, it is proposed to evaluate the customer satisfaction from timely and reliable service. Commonly, for the delivery services we can represent the task of optimization as the minimization of time in the proposed time window, minimization of energy consumption under maximization of safety. This can be represented with optimization function (1).

$$F = w(T, E, S), \tag{1}$$

$$\begin{cases} F(T, E)w \to min \\ F(S_n)w \to max \end{cases}$$

where T is a time, E is the energy consumption and S_n is safety factors (n=1...n).

w is weighed coefficient (w = 0...1).This parameter defines the impact of each of the contributors to the function and can vary depending on the UAVs mission objective or UAV type.

The set of S parameters includes variety of components. One of these components is the weather-related hazards. Therefore, the function $F(S_n)w$ can be represented as subset (2):

$$S = (NO, D, AO, AR, GR \ldots W)w, \tag{2}$$

where some of the components that define the set that influence the flight safety are NO is for natural obstacles, D is for other UAVs, AO is for artificial obstacles including buildings or wire telecommunication lines, AR is air risk, GR is ground risk and W component is component that defines weather hazards. AR and GR can be assessed as it is proposed in [31].

In turn the weather-related hazards can be again represented with the set of elements (3):

$$W = (W_1, W_2, \ldots W_n)w, \tag{3}$$

Each element in the set (3) corresponds to the particular weather phenomena. w the weighted coefficient that define the risk value connected with particular weather situation or weather phenomenon for defined type of UAV and related mission. Finally, the function that represent the safety can be given as (4):

$$F = ((NO_1, NO_2 \dots NO_n)w, (D_1, D_2 \dots D_n)w, (AO_1, AO_2 \dots AO_n)w, (AR), (GR) \dots) \times (W_1, W_2, \dots W_n)w), \quad (4)$$

Some of the components of the set (4) can be fixed for particular area of flight and time. Some of them are dynamically changed.

The weather can be denoted to the highly dynamic components of the set that provide the safety of UAS flight and mission realization. Moreover, the parameters of the atmosphere can vary over relatively short distance. Thus, the averaging data that are used for UAS flight preparation can appear to be not representative.

In Figure 1 it is possible to see the observed temperature difference measured in different points of the city. The statistics are taken from [32]. In the Figure 1, D1...D10 indicate the days of observations in the frame of observation period.

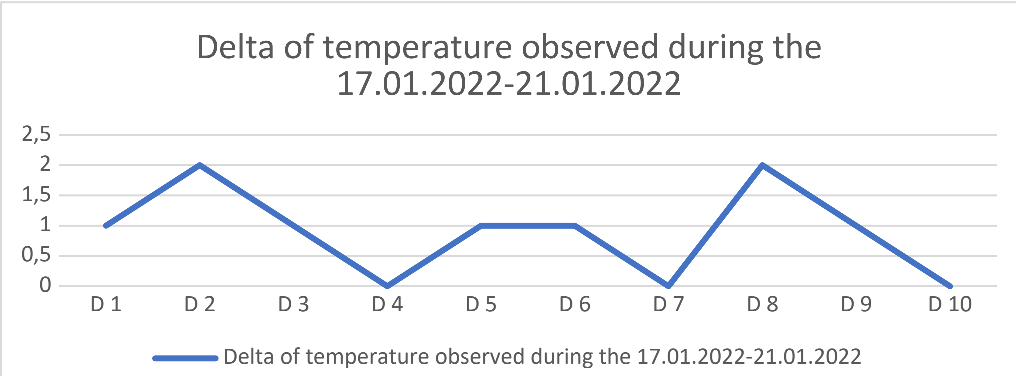

Figure 1: The temperature difference measured in two different points of the city. Nearby districts.

In Figure 2 it is possible to see the diagram that illustrates the measurements of wind taken from anemometer placed on mast and anemometer placed on UAV. The measurements were taken at different height. The statistics are taken from [33]

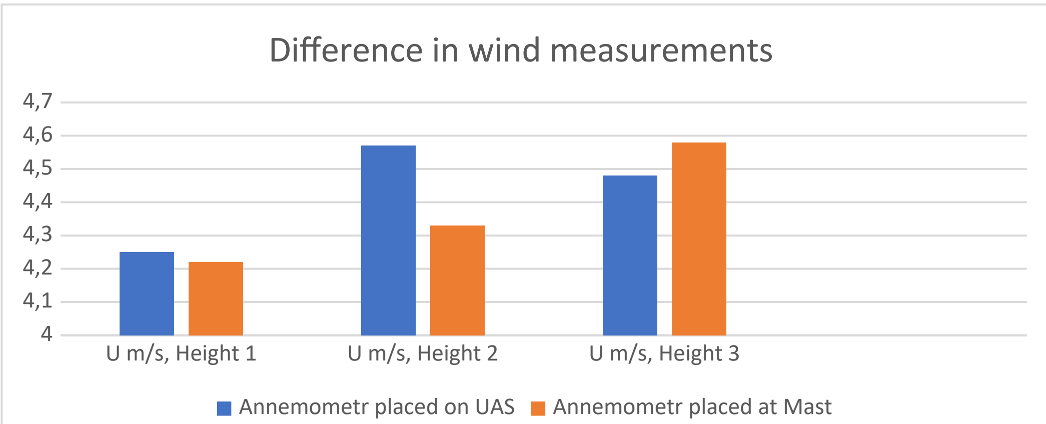

Figure 2: The measurements of wind measured in two different points of the city. Nearby districts.

It is necessary to note that usually the information about the weather is issued for particular area and does not count the local microscale variations. These variations can be crucial for UAS flight.

The presented results do not indicate the weather peculiarities or wind-related effects caused by the topography or urban constrictions. As it is known the nature or artificial obstacles can significantly change the air flow. The peculiarities of the area can create the urban wind-heat environment [34] that affects the microclimate. This, in turn, affect the UAS flight and should be taken into account when UAS urban routes planning.

5. Algorithm of prevailing severe weather areas mapping for UAS route planning

Figure 3 shows the algorithm of prevailing severe weather areas mapping that take into account the microclimatic conditions created by urban wind-heat environment for UAS route planning. The algorithm aims to minimize the impact of weather-related hazards on UAS routine missions that can be implemented in the frame of the novel concepts.

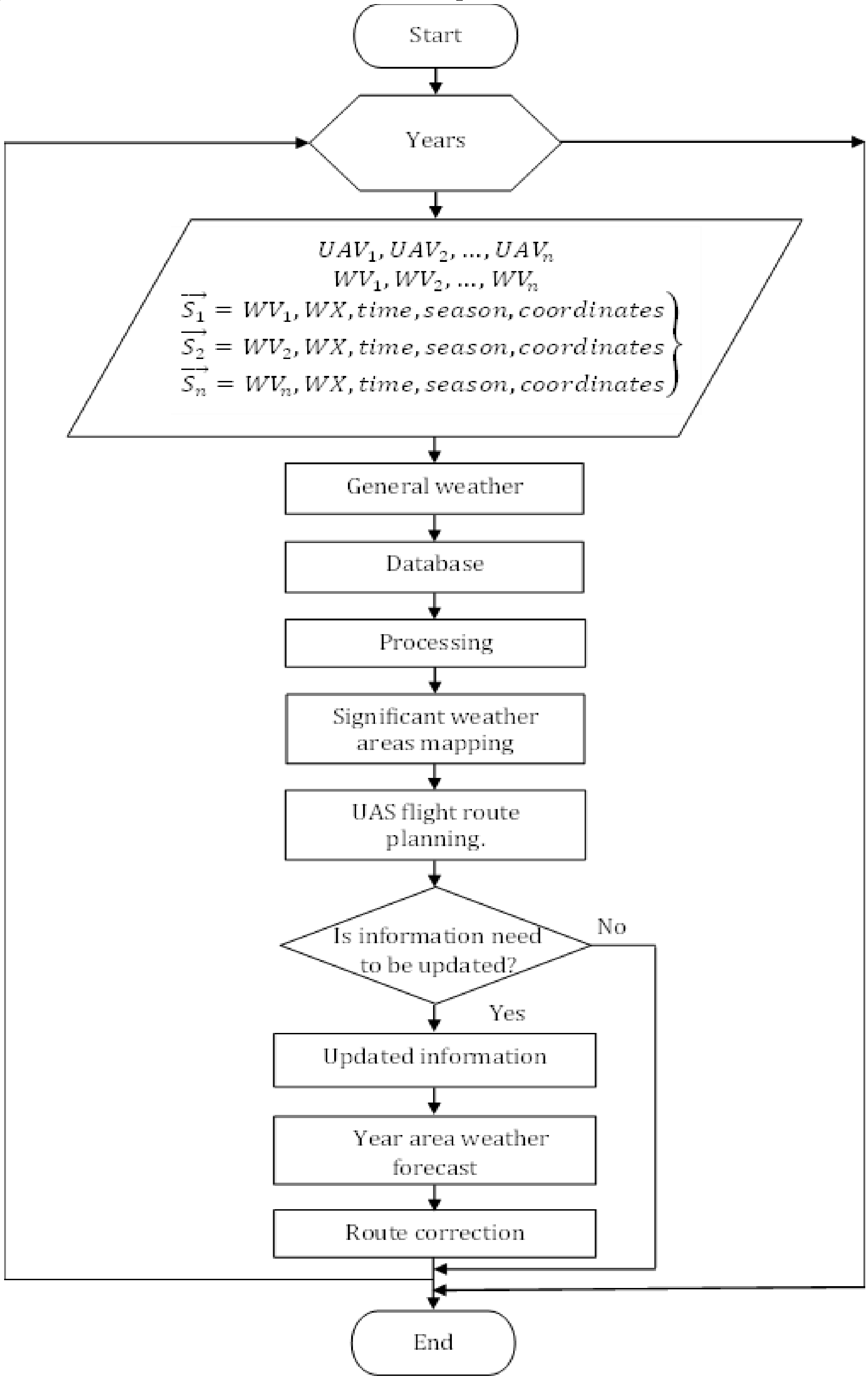

Figure 3: Algorithm of prevailing severe areas mapping for UAS route planning.

The algorithm was developed to take into account the microclimatic peculiarities of the urban area caused by the range of the factors that include:

5. general climate conditions,
6. topography,
7. characteristics of urban environment including number of buildings, their orientation, dimensions, material of constructions,
8. seasonal and diurnal weather variation.

1. The first block of the algorithm represents the data set that include

- the number of UAV performing the task represented as WV,
- wind information (represented as WV) matching the fixed point in the space ($coordinates$) and time ($time, season$)
- significant weather information r(represented as WX) matching the fixed point in the space ($coordinates$) and time ($time, season$).

2. The next step is the data collection using the information from mobile platform merges with general meteorological information for particular region. This information is the basis for the database of meteorological data for particular urban area. The volume of data is constantly replenished.
3. The third step is the processing of the collected data. The aim of the processing is preliminary identifications of the local areas of increased winds caused by tunnel effects or area of increased convection caused by the urban or topography peculiarities. The additional contribution of the urban environment into the local meteorological characteristics can be found in [35-37].
4. The step four is mapping of the area of the weather that can be considered as potentially dangerous on the spatial city map. The criteria for choice is the increased number of formation of strong and gusty winds, or convective turbulence in the particular place. These areas are considered as unfavorable for UAS flight and should be avoided when route planning. It is obviously, that seasonal variations of the weather should be taken into account to make seasonal flight route correction as well.
5. Then, the new cycle in the algorithm is organized to repeat observations for possible correction in flight route planning. This is intended to take into account the changes in climate characteristics as well as characteristics in urban topography and environment.

The question of period of observation for UAS rout planning is actual. The weather prediction model may appear useful to develop to take into account the differences that may occur from year to year.

6. Simulation of trajectory correction for route planning

On the base of proposed algorithm the simulation of trajectory correction was made. Si simulation was made on the base of situational formation of dangerous weather formation as the lack of data of long period observation for particular urban environment.

In Figure 4 the simulation of trajectory correction is present. the simulation was done using the Bellman-Ford algorithm. The flight route correction is done to avoid areas of potentially dangerous wind, and minimize the flight time and energy consumption.

We can see on the Figure 4 the preliminary flight trajectory that is marked as the “Planning Flight”. This is indicated with blue color and marked as 1. This path is planned from the criterion of minimum fuel consumption. Along this flight route the points 6,7,8 can be potentially dangerous due to the tunnel effect. On the Figure 4 this potentially hazardous area is marked with red dashed line. The alternatives are proposed to avoid these areas. The alternative flight paths are represented with yellow and orange colors correspondingly and marked as 2 and 3. The proposed alternatives are characterized with the almost insignificant increase in energy consumption, but allow to avoid potentially dangerous area.

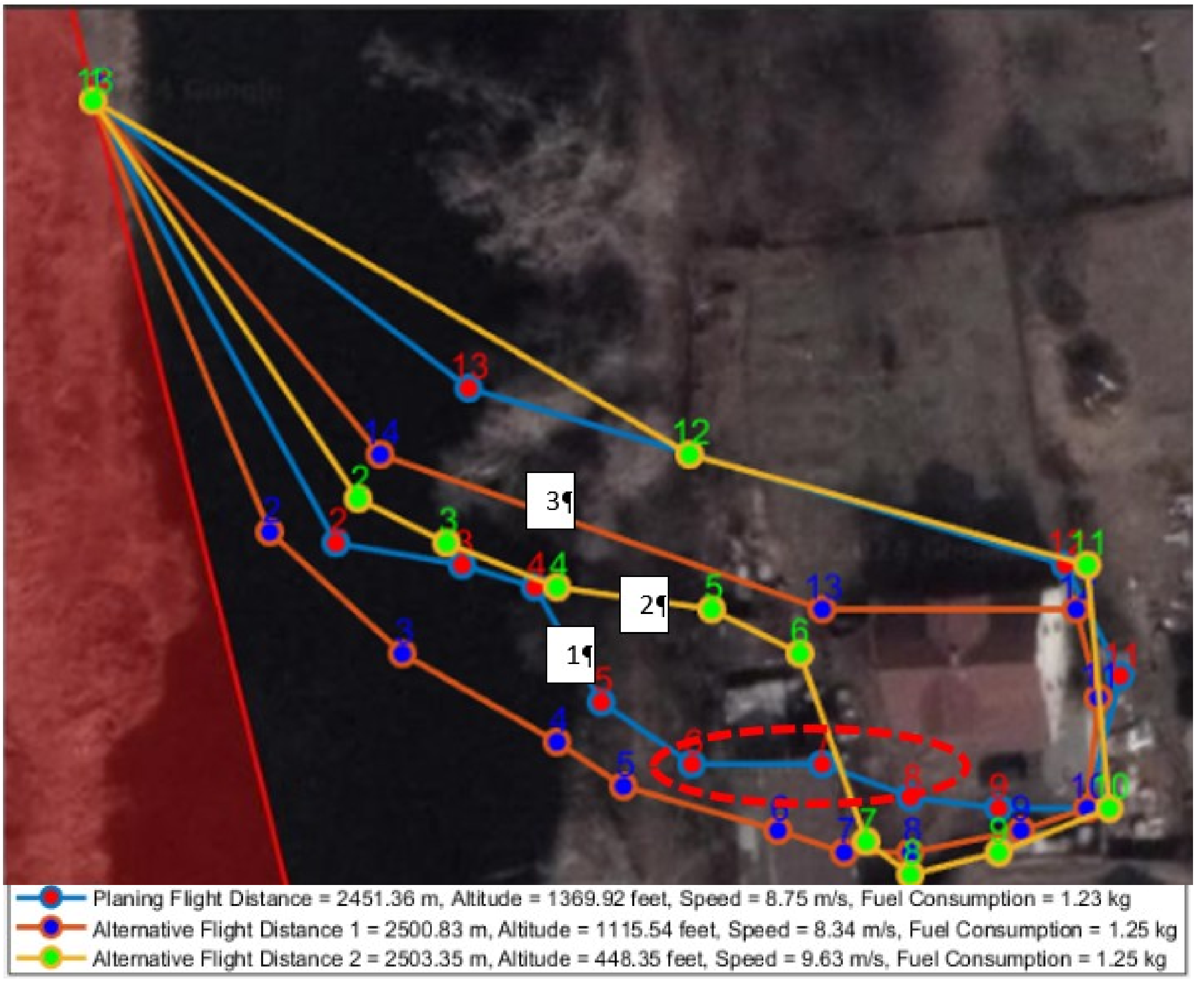

Figure 4: Simulation of trajectory correction to avoid areas of possible wind speed increase and eddies formation due to tunnel effect.

The two alternatives trajectories were analyzed as the closest to the initial flight route. The tree other trajectories that sere simulated are characterized the highest safety as demonstrate the largest distances from the dangerous place. At the same time these trajectories are characterized the largest fuel consumption.

The diagram that compare the fuel consumption and distance to the destination point for the tree trajectories is shown in Figure 5.

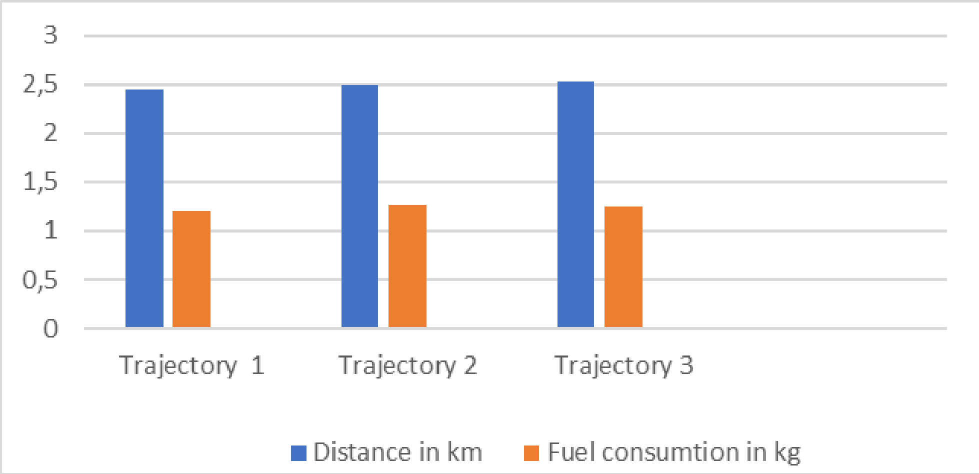

Figure 5: Comparative analysis of the trajectory's characteristics

The shortest distance and the lowest fuel consumption correspond to the planned trajectory in Figure 5. We can see from the Figure 5 The insignificant increase in flight distance and fuel consumption when following simulated trajectories 2 and 3. The fuel consumption is the same for trajectories 2 and 3 and slightly longer flight distance is for the trajectory 3 compare to trajectory 2. Analyzing the Figures 4 and 5 it is possible to say that trajectory 3 is more favorable from the safety point of view as allow total avoiding potentially dangerous area without significant loss of economic parameters of flight.

Conclusions

In this paper we consider the promising application of UAS in the frame on the novel concepts including IoT, air mobility, smart cities and society. In the frame of the concepts, UAV can be used as one of the key elements for many applications. The question arises how to organize the regular, safe, ecological and sustainable use of the unmanned aviation in the highly dynamic environment and changing weather conditions.

We propose an algorithm that allows to collect weather information for identification and mapping the areas inside the urban environment that are affected by weather conditions significant for UAVs flights with increased periodicity.

The information is proposed for use when flight route planning and scheduling. The simulation that demonstrate the flight path correction to increase the UAS operations safety is presented and discussed.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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