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Abstract: The world population is expected to grow further with major increase in population living in urban areas. Exploiting the door-to-door concept to the full extent, a considerable part of conventional vehicles may be replaced by personal aerial vehicles. Cargo delivery system will follow same philosophy using unmanned aerial vehicles. This brings up completely new challenges for future air traffic management in urban environments. The focus of the Metropolis research project is to investigate radically new airspace design concepts for the urban environments 50+ years into the future, which are extreme when compared to today in terms of traffic density, complexity and constraints. This work presents the results of simulation data analysis and comparison of concepts of urban airspace design regarding organizational (complexity) metrics. The aim was to identify how the structure involved in the concept of urban airspace design influences the complexity of the traffic situation. In this work geometrical metrics, which are only linked to trajectory structure and not to the system used to process them, were used to measure complexity. Robust extension of proximity-convergence metrics as a compound metric has been developed for the ultimate concept evaluation.

Keywords: Future urban airspace design, Traffic complexity, Metropolis, Personal Air Vehicles, Unmanned Air Vehicle

1. INTRODUCTION

According to the United Nation Population office, the world population is expected to grow from 7 billion in 2011 to 9.3 billion in 2050 [1]. What is more critical, it is expected that population living in urban areas will be doubled by that time reaching 6.3 billion [1]. Exploiting door-to-door concept to full extent, it is expected that considerable part of conventional vehicles will be replaced by personal air vehicles (PAV) [2]. Amazon, Google, DHL and other’s interested in a future delivery system using unmanned air vehicle (UAV) reveals that cargo delivery will follow same door-to-door philosophy [3] [4] [5]. This brings up completely new challenges for the future Air Traffic Management (ATM) in urban environments.

The focus of Metropolis research project was to investigate radically new airspace design concepts for the urban environments 50+ years into the future, which are extreme when compared to today in terms of traffic density, complexity and constraints. The fundamental, but still practical, question underlying this research is structure-capacity relation: Does adding structure to the airspace design increase or decrease capacity? How does it influence traffic complexity, safety or efficiency? To have better understanding of alternatives, four extreme concepts has been designed in the project [6], differing in the terms of structure and control involved. Ranging from free-flight concept with no structure involved, called Full Mix, structure is gradually increased in Layers and Zones concept until full structure is reached in the Tubes concept. Proposed concepts were implemented in a simulation program called Traffic Manager (TMX) [7], a medium fidelity desktop simulation application designed for interaction studies of aircraft in present or future ATM.
environments, and were evaluated under different scenarios of Metropolis growth. In the end over 6 million flights were simulated for which data was logged for the -processing.

This work presents the results of simulation data analysis and comparison of concepts of urban airspace design regarding organizational (complexity) metrics. Section 2 contains brief description of the concept of urban airspace design, as seen by the members of the Metropolis project consortium. Next, in the section 3 an overview of the existing complexity metrics will be presented with description of the metrics used in this paper for the data analysis. Robust extension of proximity-convergence metrics as a compound metric will be also presented here. In section 4 some result of concept evaluation and analysis, regarding complexity of traffic situation they produce, are presented and discussed. Finally the main conclusion are drawn and listed in the section 5.

2. DESIGN OF AIRSPACE CONCEPTS

This section contains brief description of the airspace concepts design. For the more detailed description please refer to [6].

Since the goal was not to design one ultimate concept, but rather investigate structure-complexity relation, four concepts have been proposed: Full Mix, Layers, Zones and Tubes, with increasing structure in mind, from the one with no structure involved up to a fully structured airspace.

2.1. Full Mix concept

Underlying assumption of this concept, that any structuring of traffic flows decreases overall efficiency of the system, is justified by the fact that traffic demand in the future urban environment will most likely be unstructured (door-to-door philosophy). Moreover, Free Flight research had shown that spreading of the traffic in airspace results in fewer conflicts which are easy to solve by cockpit crew assisted by an Airborne Separation Assurance System (ASAS), which alerts and advises the crew [8].

In the Full Mix concept, aircraft are therefore permitted to use the direct path between origin and destination, as well as optimum flight altitudes and velocities, thus reducing flight costs. Tactical control of the traffic is handled, in decentralized fashion, by automated ASAS developed in [9], allowing three types of resolution maneuvers: heading, altitude and speed change, that ensures conflict-free trajectories.

2.2. Layers concept

Based on existing principle of hemispheric flight levels, airspace in the Layers concept is separated into different vertical bands (layers) that limit allowed heading ranges (Fig. 1).

While flights are still allowed to use direct (shortest) routes, traffic segmentation reduces heterogeneity of the relative velocities between aircraft flying at the same layer, therefore reducing conflict rate. Remaining conflicts are solved using same automated ASAS with combined heading and speed maneuvers. Increased safety comes at the price of efficiency, as flights might not be able to use optimal altitude.

2.3. Zones concept

Zones concept takes step further in segmentation of the airspace compare to Layers concept. It is based on the principle that traffic is homogeneous in different zones of airspace in which traffic moves at the same speed and follows the same global direction.

A distinction is made between circular and radial zones (Fig. 2). Circular zones are similar to ring roads and allow journeys in the outer area of the city. Radial zones serve as connections between these concentric zones and enables traffic to travel to and away from the city center. Each zone is unidirectional as shown in the figure. Both types of zones segment airspace only in the horizontal plane, meaning that flights may use their optimal altitude. The horizontal path is computed at pre-tactical level using the A* shortest path algorithm. ASAS maneuvers consists of speed and altitude change in that order of priority.

2.4. Tubes concept

Finally, Tubes concept represents fully structured airspace concept that is based on assumption that provided conflict-free 4D tubes for each flight at pre-tactical level, both safety and efficiency of the flight could be increased.
In the Metropolis implementation of the Tubes concept a fixed route system is design, and a time-based separation is used to have pre-planned conflict free routes. Tubes topology is based on a diagonal grid layout consisting of edges (tubes) and vertices (nodes) as on Fig. 3. In order to take advantage of the 3D airspace, a number of tube levels of decreasing granularity are foreseen. For route planning, the A* depth-first search algorithm is used to plan the shortest trajectory from origin to destination, prior to departure.

3. COMPLEXITY METRICS

This section presents the overview of the existing complexity metrics and describes metrics used in the Metropolis project to compare different concepts of urban airspace design.

3.1. Scope

Future urban transport is a safety critical system and maintaining safe separation between vehicles and with other obstacles is imperative for the system. When a conflict is detected, a resolution process is launched which, in certain situations, may generate new conflicts. This interdependency between conflicts is linked to the level of mixing between trajectories. In addition, uncertainty with respect to positions and speeds increases the difficulty of predicting future trajectories. The difficulty to control a system depends on both its sensitivity to initial conditions and interdependency of conflicts [10].

One of the research goals of the Metropolis projects was to identify how the structure involved in the concepts influence the complexity of the traffic situation. Measuring and comparing complexity of the resulting traffic situations, it is implicitly possible to compare how difficult it is to control a given system. In addition measuring the robustness will determine how much the system is invariant to changes in the initial conditions and also external influences.

3.2. Overview of existing metrics

Research into air traffic complexity metrics has attracted considerable attention in recent years. Proposed models can be grouped into two groups: the first one focused on the air traffic control officer (ATCo) workload, and the second one focus on traffic complexity using automatic conflict resolution algorithms.

The first group of models has objective to model the control workload associated with given traffic situations. The main approaches are as follows. In model based on traffic level [11], the workload is defined as the proportion of control time (duration of control actions taken to resolve conflicts) over an hour. Queue-based model [12] considers control sector as a system supplying service and queuing theory is used to determine a maximum acceptable arrival rate for a sector. Models based on airspace structure [13] [14] estimate the capacity and complexity of a sector based solely on its structure (flight levels, routes, route intersections, etc.). In the context of operational control, the ideal option would be to find a metric which precisely measures cognitive difficulty to manage a certain situations. There are various reviews that have been studying factors that impact upon controller workload and their relation to the workload experienced by a controller. The list of factors includes numbers of traffic and airspace characteristics like: total number of airplanes, minimum distance between airplanes, number of changes in direction, speed and altitude, number of predicted conflicts, etc. In NASA, Dynamic density model [15] [16] [17] is developed as a weighted sum of traffic complexity factors. In [18] a multivariate analysis based upon simulation modelling is proposed. However listed models are not generalized and are linked to studied sector structure and sensitive to controllers used to infer the model.

Other approaches [19] [20] model the complexity of a traffic situation using automatic conflict resolution algorithms, for which the number of trajectory modifications required in processing a given situation is measured. In the same way as before, these methods are highly dependent on the type of algorithm used to resolve conflicts.

Airspace concepts, presented in section 2, differ in the level of structure and ways how system is managed and controlled. For this reason, previously listed approaches are not suitable as it is necessary to use an intrinsic traffic complexity metric that is only linked to trajectory structure, and not to the system used to process them. In next section some geometrical metrics, presented in [10] [21], are studied and robust extension of proximity-convergence metric is elaborated.

3.3. Geometrical approaches

These metrics are calculated at a given instant using the positions and speed vectors of airplanes present in the chosen geographical zone. Each of these geometrical metrics exhibits a particular characteristic associated with the complexity of the situation.
The risk associated with the convergence of the trajectories of all pairs of airplanes is normalized by their value in the horizontal and vertical planes (e.g., 5NM and 1000 ft).

3.3.1. Proximity indicator

The proximity indicator is used to characterize the geographical distribution of airplanes in the given volume of airspace. It allows us to identify spatial zones with high levels of aggregation in relation to their volume. Thus, for a constant number of airplanes in a sector, proximity is used to distinguish whether these airplanes are distributed homogeneously (Fig. 4a) or in the form of clusters (Fig. 4b).

For two airplanes $i$ and $j$, proximity is calculated as a weighting coefficients given by formula (1).

$$ P_{ij} = f(d_{ij}) = e^{-αd_{ij}^2}, $$

where $α$ is a parameter fixed by the user, and $d_{ij}$ is normalized distance between airplanes.

3.3.2. Convergence indicator

The convergence indicator is used to quantify the geometric structure of the speed vectors of airplanes in the given volume of airspace. Thus, for identical proximity values, the convergence indicator allows us to distinguish between converging (Fig. 5, red arrows exp.) and diverging (Fig. 5, green arrows) airplanes.

For two airplanes $i$ and $j$, the level of variation of their relative distance is given by the formula (2), and they converge if, and only if, this level of variation is negative.

$$ C_{v_{ij}} = \frac{d}{dt} (d_{ij}) = \frac{\vec{v}_{ij} \cdot \vec{d}_{ij}}{d_{ij}}, $$

where $\vec{p}_{ij}$ and $\vec{v}_{ij}$ represent relative position and speed vectors respectively.

3.3.3. Proximity-convergence metric

In reality, the risk associated with the convergence of a pair of airplanes also depends on the relative distance between them [21]. We must, therefore, simultaneously account for the speeds and relative distances of each pair of airplanes.

For the given time and for each airplane under consideration, we open a spatial weighting window centered on that airplane. Then, complexity metric associated with referenced airplane, as in (3), is calculated adding together factors of all pairs of airplanes in the reference window.

$$ C_{X_i} = \lambda \sum_{j/\cap \neq 0} -C_{v_{ij}} \cdot e^{-αd_{ij}^2} $$

3.3.4. Robust extension of the metric

The geometrical approaches presented so far use noiseless observations, allowing us to generate instantaneous metrics. Due to possible change in initial conditions (delay) and external issues (wind, disruptions, regulations, etc.), the stochastic aspect of observations need to be taken into account in order to generate reliable (robust) metrics. To do this, trajectory observations, computed through simulation using a set of flight plans, are affected by noise, particularly in the temporal dimension. In the context of stochastic process theory, this phenomenon is known as clock shifting: “the trajectory continues to conform to the flight plan in the spatial dimension, but the position of the vehicles on the trajectory may be subject to significant deviations in the temporal dimension [22]).

Robust complexity metric for a given airplane at a given time is computed taking into account all possible pair of observations of airplanes existing in spatiotemporal window centred on referenced airplane (Fig. 6). Red lines in the figure indicate all possible pair of observations between planes $i$ and $j$. Complexity associated with an airplane $i$ with respect to plane $j$ at a given time $t$ is computed as an time averaging of the proximity-convergence metric over all pairs of observations ($t - \Delta t ≤ t ≤ t + \Delta t$) and it is given by formula (4).

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1 Due to the fact that separation norms are not the same in the horizontal and vertical planes distance is normalized by their value (e.g. 5NM and 1000ft)
\[ C_{x_{ij}} = \frac{1}{m_{ij}} \sum_{t_{ij} \in t_{ij}} \sum_{n_{ij} \in n_{ij}} -C_{v_{ij}}^{r_{ij}} \cdot e^{-\lambda d_{ij}^2} \]  

(4)

where \( C_{v_{ij}}^{r_{ij}} \) and \( d_{ij}^{r_{ij}} \) represent variation of relative distance and normalized distance of airplane \( i \) at the time \( t_i \) and airplane \( j \) at the time \( t_j \), while \( m_{ij} \) is number of observation pairs.

Robust complexity metric associated with airplane \( i \) is computed as the sum over all pairs of planes in the spatiotemporal window by (5).

\[ C_{x_i} = \lambda \sum_{j/C_{x_{ij}} \geq 0} C_{x_{ij}} \]  

(5)

Finally, complexity of the given traffic situation at a given time is then calculated using the sum of the robust complexity metrics of the airplanes present in that geographical zone for the given time.

4. SIMULATION DATA ANALYSIS

To compare the four airspace concepts in terms of complexity, large-scale simulation experiments were performed. Proposed concepts were implemented in a simulation platform called Traffic Manager (TMX) [7], medium fidelity desktop simulation application designed for interaction studies of aircraft in present or future ATM environments, developed by NLR.

4.1. Experiment design

Metropolis scenarios were design for the fictional city based on the present-day Paris 50 years in the future. Similar to other modern cities, the zoning also applies to the fictional Metropolis city that is divided into three major districts: city center, inner ring and outer ring, with specific land-use.

Based on different predictions of population growth (14-26 million) and travel demand assumptions, four scenarios were computed differing in the traffic volume: low, medium, high and ultra-high volume scenario. In addition to multiple traffic volumes, due to zoning, different traffic demand patterns were experience during course of the day, respectively: morning, lunch and evening period scenario. Furthermore, the scenarios were simulated with and without the ASAS enabled, in order to study the effect of the airspace structure itself on the operations: structure vehicle separation ability. Finally, taking into account that probabilistic distribution function is used for flight’s origin-destination pair computation, there were two repetitions of each designed scenario. In the end over 6 million flights were simulated for which data was logged for the processing.

For more detail about simulation platform, design of the Metropolis city and traffic scenarios please refer to [6].

4.2. Results

Due to the fact that there are many independent scenario variables, like: traffic volume, period of the day, usage of ASAS, to analyze their effects it is necessary to perform multiple tests for which all except one variable would be fixed. Following sub-sections present the most relevant results of the concepts evaluation.

4.2.1. Comparison according to traffic volume

For this analysis all concepts are compared under same period of a day, with ASAS enabled, according to four different traffic density levels: low (10,979 flights), medium (14,116 flights), high (17,253 flights) and ultra-high (20,390 flights) density. Lunch period scenario has been chosen to minimize effect of traffic pattern (distribution of the flight types) on the results due to moderate distribution in this period. However, test shown that effect of traffic density is equally significant for other periods.

Fig. 7 shows full complexity distribution (min, max, median values and interquartile range – IQR) for four airspace concepts and four traffic volumes. Several general conclusions can be drawn. Main conclusion, as it was expected, is that traffic complexity increases with traffic density for all concepts. The complexity increase is caused by increase of both: proximity and convergence as shown in the Fig. 8 for the Layers concept².

² Similar figures are found for other concepts.
This is expected, as with increase in traffic volume, for the same airspace, vehicles come geographically closer increasing proximity, while trajectory intersections increase convergence metric.

Another observation from the Fig. 7 is the order of concepts by the increasing level of complexity: Tubes, Layers, Full Mix and Zones, that is preserved with traffic volume. The order is based on comparison of average complexity values, which is relevant taking into account size of the confidence intervals that are rather small.

Having in mind initial idea of the Tubes concept to design conflict-free 4D route of the flights at pre-tactical level (when flights are spawn), complexity results are not surprising. Time separation between flights at crossing points reduces both convergence and proximity metrics, and therefore reduces traffic complexity making Tubes concept best performed one.

Layers and Full Mix concepts are both based on direct routing principle, with the difference that in the Layers concept cruising altitude is prescribed for a given headings. The fact that at each flight level, in the Layers concept, flights are homogenous in flight direction reduces flight convergence compared to Full Mix concept. In addition, choice of cruising level, based on flight direction, increases the usage extent of the vertical dimension of the airspace. Additional vertical separation of flights reduces traffic proximity, which in combination with lower convergence result in lower traffic complexity for Layers concept than Full Mix concept.

Finally, Zones concept had significantly poorer performance regarding complexity compared to other concepts. Explanation for this is in the Zones concept structure design that consists of concentric rings and radials. The radials converge to the city centre causing higher concentration (higher proximity) of the traffic in the core city area. In addition, traffic is structured only in the horizontal dimension and not separated in the third dimension creating high convergence areas around structural crossing points (ring and radial intersections). It is expected that different Zones concept design might result in a better traffic complexity. However, general conclusion is that introduction of the higher structure into airspace without involvement of traffic management in general result in the higher traffic complexity.

Although relation of complexity increase and increase of traffic density looks linear from Fig. 7, as the increment between low, medium, high and ultra-high densities is not linear, there is polynomial relation between traffic complexity and density. Fig. 9 shows almost quadratic relation between complexity and density for all concepts except Tubes concept.

This is due to the fact that route planning algorithm in the Tubes concept reject some flight plans if it is unable to find conflict free 4D route, that happens at high traffic volumes. Although not great in numbers, rejected (removed) flights are usually the most critical ones (the ones that cause the most problems), which have significant effect on the complexity.

Final analysis of the traffic volume effect includes robust complexity metric. Taking into account robustness, the order of the concepts by the increasing level of complexity changes to: Layers, Full Mix, Zones and Tubes, as on Fig. 10. Other than Tubes, order of concepts is not changed, leading to a conclusion that Layers, Full Mix, and Zones produce traffic situations with similar level of robustness. On another hand, Tubes concept shows very low level of robustness and therefore is highly influenced by changes in the initial conditions. Similarly to general metrics case, results show correlation between traffic density and robust complexity that increases with density.

4.2.2. Comparison according to period of the day

For this analysis all concepts are compared under the same highest level of traffic density (ultra-high scenarios), with ASAS enabled, according to different rush-hour periods of the day: morning, lunch and evening period.

Fig. 11 shows full complexity distribution (min, max, median values and interquartile range – IQR) for four airspace concepts and three period of the day.
First conclusion is that the order of the concepts by the increasing level of complexity doesn’t change with period of the day and is the same as the order shown in previous analysis for the general complexity metric: Tubes, Layers, Full Mix and Zones.

Traffic volume, to small extent, differs between rush-hour periods, increasing in following order: lunch, morning and evening period. For the Layers and Full Mix concepts, this increase in the volume is followed by the small increase in the traffic complexity and is in accordance with effects of traffic volume on complexity shown in previous sub-section. However, Zones and Tubes show an exception from general rule.

It can be noted that complexity of the Tubes concept at the evening period is even reduced compared to other periods, although it represents period with highest traffic volume. This is once again the effect of the rejected flights for which conflict free 4D route wasn’t available at the time when they had been spawned.

Also it can be noted that increase of traffic complexity for the Zones concept at evening period, compare to other periods, is not in accordance with traffic volume increase for this period. In fact, increase of Zones concept complexity is significantly higher. Zones structure effect on the complexity, alone, is not enough to explain such increase and the explanation is in the traffic structure. In addition to higher traffic volume, evening period is characterized by high supply of commercial areas: commercial-residential (e.g. people going home) 55% of traffic and commercial-commercial (e.g. people going shopping after work) 20%. As commercial areas are mostly located in the core city area, this results in high traffic density in the city center immediately after flight departure. Having fixed structure without possibility to delay flights, Zones concept produces highly complex traffic situations at evening period (Fig. 12a). Although there is high demand for the commercial areas in the morning period (60% of flights), the resulting traffic complexity is lower as flights are partly sequenced by the structure before reaching core city area (Fig. 12b).

Analysis of the robust complexity metric shows similar conclusions with even more expressed effect on the traffic complexity at evening period for the Zones and Tubes concepts. However, order of the concepts changes once again to: Layers, Full Mix, Zones and Tubes, showing low level of robustness for Tubes concept.

4.2.3. Effects of the ASAS

All the previous analyses are based on simulated data with ASAS enabled. This section studies the effects of ASAS itself on traffic complexity.

Fig. 13 shows summary of the concept comparison according to traffic density with and without ASAS enabled at the lunch rush-hour. Darker colors in the figure represent scenarios with ASAS enabled; while lighter represent scenarios without ASAS enabled.

The general conclusion is that complexity increases if conflicts remain unsolved. This is expected as in conflicts aircrafts come closer together which increases traffic proximity. Also intersecting routes in conflict cause higher convergence of the traffic. In total this result in higher traffic complexity.
The order of the concept by the increasing level of complexity remains unchanged when ASAS is disabled and there is almost proportional increase (around 70%) in complexity for Full Mix, Layers, and Zones concepts for all time periods. That is not a case for the Tubes concept. The reason is in traffic separation that is attained in the route planning phase. Therefore there are no additional conflicts left unsolved for the ASAS.

In addition, Fig. 13 reveals that increase of complexity average value is followed by increase of dispersion, except for the Tubes. The same can be concluded in the Fig. 14 that shows comparative view of complexity time function for the lunch ultra-high density scenario with/without ASAS enabled. Since ASAS controls traffic geometry, by spreading the traffic, it balances complexity over time (Fig. 14a). This is not the case when ASAS is disabled, and beside overall complexity increase, Fig. 14b shows saw-like complexity function with rapid changes for all concepts except Tubes.

5. CONCLUSIONS

Based on different scenarios and different complexity metrics following conclusions are made.

When general metrics are considered Tubes concept perform best, and the list of the concepts order by increasing level of complexity is as follows: Tubes, Layers, Full Mix and Zones concept. This order is preserved at all periods of the day and for all traffic densities. Traffic complexity increase with traffic density shows almost quadratic relation for all concepts except Tubes. Tubes performs equally good as Layers and Full Mix concepts on lower traffic densities, while its performance is increased for high traffic volumes compare to other concept. This is because Tubes route planer assigns conflict-free 4D tube for each flight at departure, making complexity of Tubes less influenced by traffic volume. Moreover, Tubes route planer rejects flights when unable to assign conflict-free 4D route, which mostly happens at high traffic density.

Order of the concept by increasing level of complexity is changed when robust complexity metric is considered, as follows: Layers, Full Mix, Zones and Tubes concept.

The most important finding is that Tubes concept performs far worse when robustness is considered compared to general metrics case. This is due to the fact that robustness considers stochastic aspect of observations that are affected by the noise, particularly in the temporal dimension. Since time is the main mean of flight separation in the Tubes concept, Tubes fixed 3D structure only causes additional convergence of the flights rather than separating flights. Except Tubes, order of the other concepts is not changed when robust metrics are used, leading to a conclusion that Layers, Full Mix, and Zones concept produce traffic situations with similar level of robustness. On another hand, Tubes concept shows very low level of robustness and therefore is highly influenced by changes in the initial conditions.

Full Mix, Layers and Zones concepts show an almost proportional increase (around 70%) in complexity when ASAS is disabled. Complexity increases if conflicts remain unsolved, as expected, because in conflicts aircrafts come closer together which increases traffic proximity. Also intersecting routes in conflict cause a higher convergence of the traffic, all resulting in higher complexity. However, that is not a case for the Tubes concept, because of traffic separation that is attained in the route planning phase.

The final conclusion is that, regarding complexity, fully structured concept (Tubes) performs best when
robustness is not considered. Although future urban transport system is expected to be more predictable as compliance with the give route should also increase, dose of uncertainty will always exist. Ultimately, Layers concept is chosen as the best concept regarding complexity. It is the most robust concept which performance remains stable for all periods of the day and all traffic densities. It represents a good balance between fully unstructured and structured concept, where structure involved additionally separate flights compared to the unstructured concept (Full Mix) but doesn’t cause traffic concentration as in structured concepts (Zones, Tubes).

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