

AIR TRAFFIC COMPLEXITY: AN INPUT-OUTPUT APPROACH

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Abstract

This paper addresses a new method for describing the air traffic complexity of a given traffic situation. Air traffic complexity is defined as “how difficult” a given traffic situation is, in terms of the control activity required to resolve it, in response to an additional aircraft entering the airspace. For this, we describe an input-output framework, and present a “complexity map” that clearly provides the effective complexity for a given traffic situation. This complexity map can address airspace with an arbitrary number of aircraft. We also discuss how to extract a scalar measure of air traffic complexity from the complexity map. We illustrate our methodology with a few examples relevant to dynamic airspace management.

Introduction

The Air Traffic Management (ATM) system provides services for safe and efficient aircraft operations to transport people and goods [1]. The airspace is divided into sectors, and aircraft within each of those sectors are controlled by human controllers. Increased demand on the air transportation system increases congestion in the airspace. Therefore, much effort has been put into increasing airspace capacity. One of the main efforts has been to develop advanced Traffic Flow Management (TFM) techniques regulating traffic flow. However, one of main constraints is traffic complexity in the airspace [2]. A related effort to increase airspace capacity is called Dynamic Airspace Configuration (DAC) [2]. The operating concept of DAC is that airspace managers can reconfigure the airspace, e.g., allocate and de-allocate in accordance with the users’ demands [2] and the traffic complexity inside the sector. Even in a free flight environment, the ATM system should be capable of preventing aircraft from entering any locally complex areas in which separation may be difficult to achieve without excessive control activity [3].

Therefore, a key research problem is to quantify the complexity inside sectors or in one region of the airspace (which we will call a sector hereinafter). We define the complexity of given traffic situation in terms of the difficulty to control it. Despite efforts devoted to measuring air traffic

complexity, there is no one generally agreed upon definition [1,4,5,6,7,8,9,10]. A simple count of the number of aircraft in the sector does not address the impact of the configuration of the air traffic. Likewise, attempts to relate air traffic complexity to the subjective difficulty perceived by a human air traffic controller may derive measures that are referenced to controllers’ mental models, which can be idiosyncratic and situation specific.

Other methods to assess complexity examine the geometric attributes. One introduced metrics related to the disorder of the traffic based on relative aircraft positions and velocities [4]. Another used the fractal dimensions of the traffic flows, while still another used topological entropy as a complexity metric after modeling the airspace as a dynamical system [6,16]. However, they consider only limited aspects of the system.

Thus in this paper we use the term ‘complexity’ to reflect the minimum control activity required of the aircraft to resolve any conflicts, recognizing that, in many operating concepts, this resolution will be determined and commanded by the air traffic controllers

We describe an input-output framework to analyze the airspace and present a complexity map that clearly displays the effective complexity of a currently-conflict-free airspace in response to aircraft entering at any heading and location. Building on the seminal work of John Andrews (Lincoln Laboratory) [15], we will suggest how to interpret the complexity map.

In the first part, we will explain the method, and provide a detailed input-output system framework. We will give some numerical examples to demonstrate approach. Finally we will discuss applications of the method.

Input-output approach

Definitions

A sector is currently a part of the airspace that is managed by human controllers. However, in some future air traffic management concepts, we may need to measure local traffic complexity independent of geographic sector boundaries. This type of complexity is called Gaggle Density [3]. In this paper, we use the following definition of a sector.

Definition 1: A **sector** is a local area of airspace for which we measure air traffic complexity. It could be defined by fixed geographic boundaries or around a “gaggle” of aircraft □

We note that, if a sector is too complex, accepting an additional aircraft into the sector will require excessive control activity. On the other hand, if a sector can accept new aircraft easily, we may consider its traffic situation as not complex.

Definition 2: **Air traffic complexity** is a measure of the control activity required to accept an aircraft entering into the sector. In this paper we measure control activity by the total change in heading summed over all aircraft in the sector. However, the method allows for alternate measures including non-linear weighting of heading changes (e.g., not including heading changes under a threshold considered to be negligible) or the inclusion of other control activities such as speed and altitude changes. □

Definition 3: A **base input** is any hypothetical aircraft entering the sector of interest at any heading and location. □

Input-output system formulation

We consider airspace as a closed loop input-output system consisting of aircraft inside the sector and controllers, as shown in Figure 1. We evaluate the complete set of base inputs, i.e., any possible entering aircraft. Then we perform input-output analysis. Thus we produce a complexity map that clearly displays the state of the system in relationship to the control activity required to accept entering aircraft

An advantage of this method is its extensibility. We can include not only traffic factors, e.g., the position of aircraft, but also external environmental factors, e.g., localized weather and partial boundary closures.

For simplicity, this paper considers only the horizontal motion of aircraft. Even though vertical maneuvers are often more efficient, horizontal maneuvers are better in terms of passenger comfort and elimination of changes in flight level [12]. However, this formulation does not preclude more extensive models.

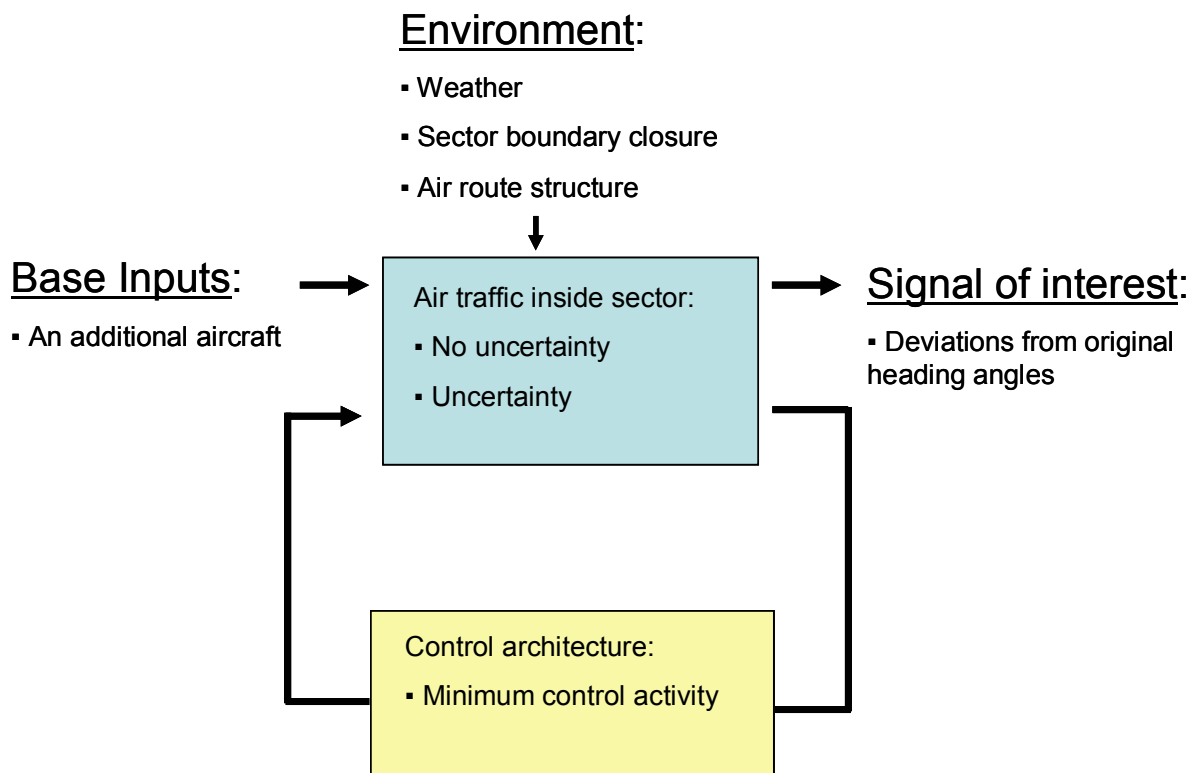


Figure 1. Input-output formulation

Details of the plant

Each pair of aircraft is forbidden to be closer than permitted by safety regulations. In order to avoid such conflicts, each aircraft is allowed to change its heading angle in one impulsive change. Aircraft can have different constant velocities. For brevity, the examples show aircraft at the same velocity and the sector boundary is approximated by a circle. The following 2-D kinematical model is used for each aircraft.

$$\dot{x} = V \cos \theta_i, \quad \dot{y} = V \sin \theta_i, \quad \text{where } i = 1, 2, \dots, N \quad (1)$$

Control architecture

The optimal control method to identify minimum control activity has been fully documented in the previous paper [13]. As a brief summary, the problem can be formulated as a mixed integer linear programming problems and can be solved by some fast optimization tools, e.g., CPLEX [14].

In Fig. 2, the circle around each aircraft represents its safety region. No safety region should intersect with another. For this, the direction of the relative velocity vector of aircraft 1 with respect to aircraft 2, i.e. $V_{1/2}$, should satisfy certain conditions. These conditions depend on the relative heading angles of each aircraft, i.e. $q_{1/2}, q_{2/1}$. For example, if $0 \leq q_{1/2}, 0 \leq q_{2/1}$ and $q_{1/2} \leq q_{2/1}$, then the following conditions should be satisfied.

$$\theta_s \leq \left| -\frac{\pi}{2} + \frac{1}{2}(q_{1/2} + q_{2/1}) \right| \quad (2)$$

$$\theta_s = \arcsin\left(\frac{2L}{R_{12}}\right) \quad (3)$$

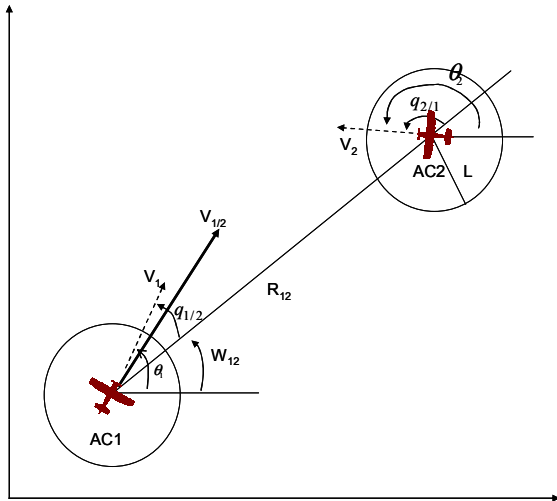


Figure 2. Conflict geometry

Note that different configurations between aircraft require different non-conflict conditions. Likewise, aircraft trajectories are represented by absolute headings of the aircraft relative to true north, θ_i , instead of $q_{i/j}$ in multiple aircraft scenarios because $q_{i/j}$ are relative quantities for each pair of aircraft.

The relationship between θ_1 and $q_{1/2}$ is:

$$q_{1/2} = \theta_1 - W_{12} - 2\pi S_{12} C_1 \quad (4)$$

$$S_{12} = -\text{sgn}(W_{12}) \quad (5)$$

C_1 is the binary variable. These integer variables should be introduced because non-conflict conditions are derived in the confined solution space, e.g. $-\pi \leq q_{1/2} \leq \pi$ and $-\pi \leq \theta_1 \leq \pi$. Similarly, we can derive the whole set of non-conflict constraints for all aircraft.

If there are conflicts between aircraft, some of them should change their heading angles to satisfy non-conflict conditions. Among the many possible solutions, we choose the one that minimizes the following objective function as our measure of the minimum control activity required, i.e. complexity.

$$\text{Cost function} = \sum_{i=1}^{i=n} |\theta_{in} - \theta_i| \quad (6)$$

Where θ_{in} is the new heading angle for each aircraft. Other objective functions may be defined as appropriate.

Details of the input

As explained in previous sections, an aircraft entering the sector is considered as a base input into the system. Some notations are needed for the incoming aircraft, illustrated in Figure 3.

Definition 4: The **entering aircraft position angle** defines the entry point of the aircraft into the sector as an angle representing its position relative to the sector center. □

Definition 5: The **entering aircraft bearing** defines the relative track of an entering aircraft with respect to the line connecting the aircraft to the center of the sector. A bearing of zero means that the incoming aircraft is moving toward the center of the sector. Figure 3 illustrates a positive bearing. □

A complete set of inputs encompasses all possible entering angle position angles and bearings. For a circular sector boundary admitting aircraft from any direction, the intruder position angle spans 0 to 360° and the intruder bearing angle spans -90° to 90°.

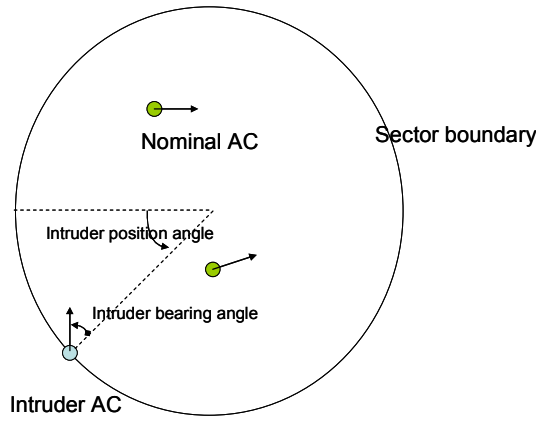


Figure 3. Notations for an aircraft entering the sector

Numerical examples

The two airspaces configuration in Figure 4 and 5 will be investigated to demonstrate this method. The large circles represent sector boundaries and the small circles demarcate the safety regions around aircraft. The velocity vectors of the aircraft are indicated by the line segments originating from the aircraft locating at the center. The initial configurations of traffic in both airspaces are conflict free.

Complexity map

For each particular value of an entering aircraft's position angle and bearing angle into the sector, the minimum value of the heading changes required of all aircraft to maintain a conflict-free situation is identified, as defined in (6). If no conflict arises from the entering aircraft, this value is zero.

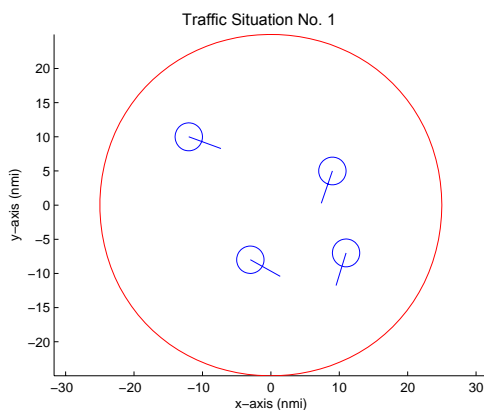


Figure 4. Traffic situation 1

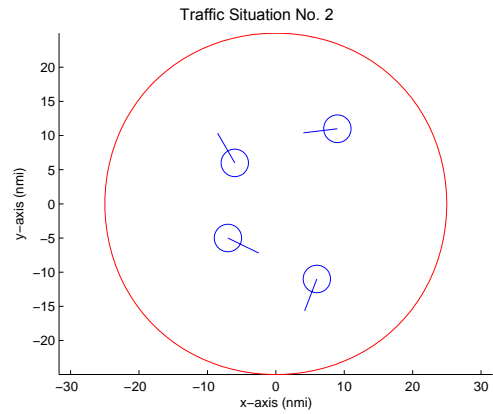


Figure 5. Traffic situation 2

The loci of these values over all possible entering aircraft position angles and bearings can be displayed as a complexity map of the immediate traffic situation. Such complexity maps are shown for traffic situations 1 and 2 in Figures 6 and 7, respectively. Here, we see that traffic situation 2 requires control activity over a noticeably larger range of entering aircraft position and bearing angles, compared to traffic situation 1. However, the largest control activity that an entering aircraft can demand in traffic situation 2 exceeds only 40° , while for traffic situation 1 it can, for a range of entering aircraft position angles between 120° and 150° and bearing angle between 0° and 25° , exceed 70° .

Let's consider a particular incoming aircraft in traffic situation 1 in more detail. The control activity required of this entering aircraft is represented on traffic situation 1's complexity map by \odot in Figure 8.

(1) A heading change by the entering aircraft causing an increase in its bearing relative to the sector is represented by the vector O/CC . Tracing this vector, we find that a small increase in entering aircraft bearing can result in zero required control activity by the aircraft currently within the sector, i.e., will keep the sector conflict free. In contrast, even a large decrease in bearing, shown by the vector O/C , will still require significant control activity within the sector.

(2) An entry position change by the entering aircraft causing a decrease in its position angle is represented by the vector C/O . Tracing this vector, we find that a small decrease in the entering aircraft's position angle can result in zero required control activity. In contrast, more increase in position angle, shown by the vector CC/O , is required to keep the sector conflict free. Assuming that position angle and bearing are of equal difficulty to adjust, the best way to keep the sector

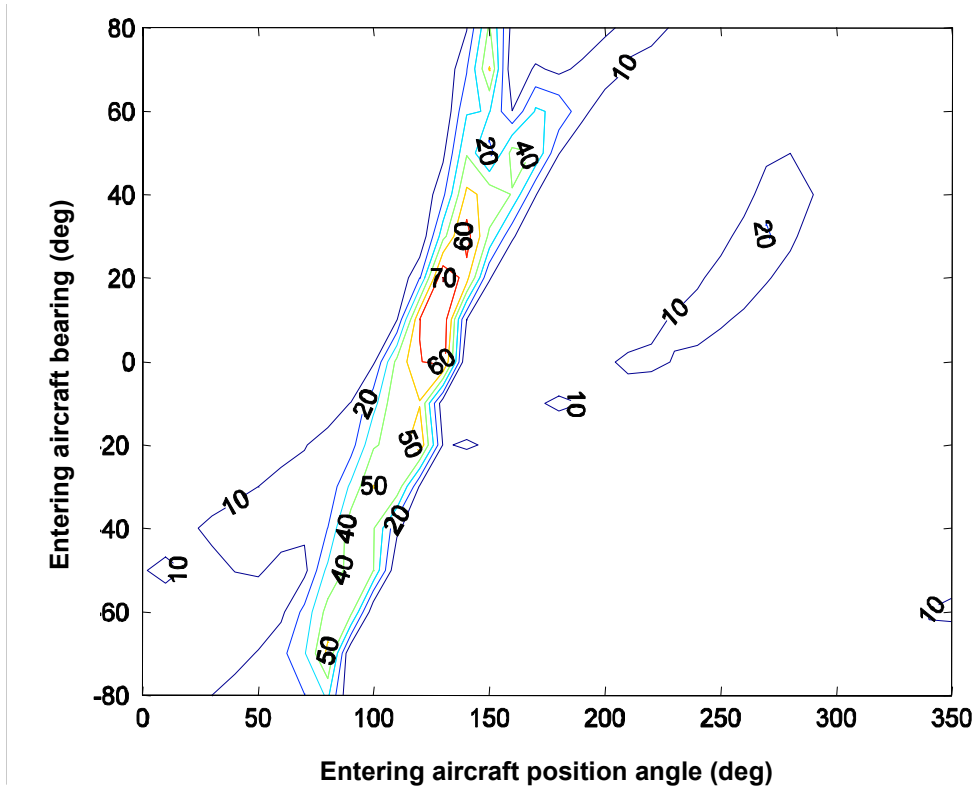


Figure 6. Complexity map for traffic situation 1, indicating contours of minimum control activity for all combinations of entering aircraft bearing and position angles

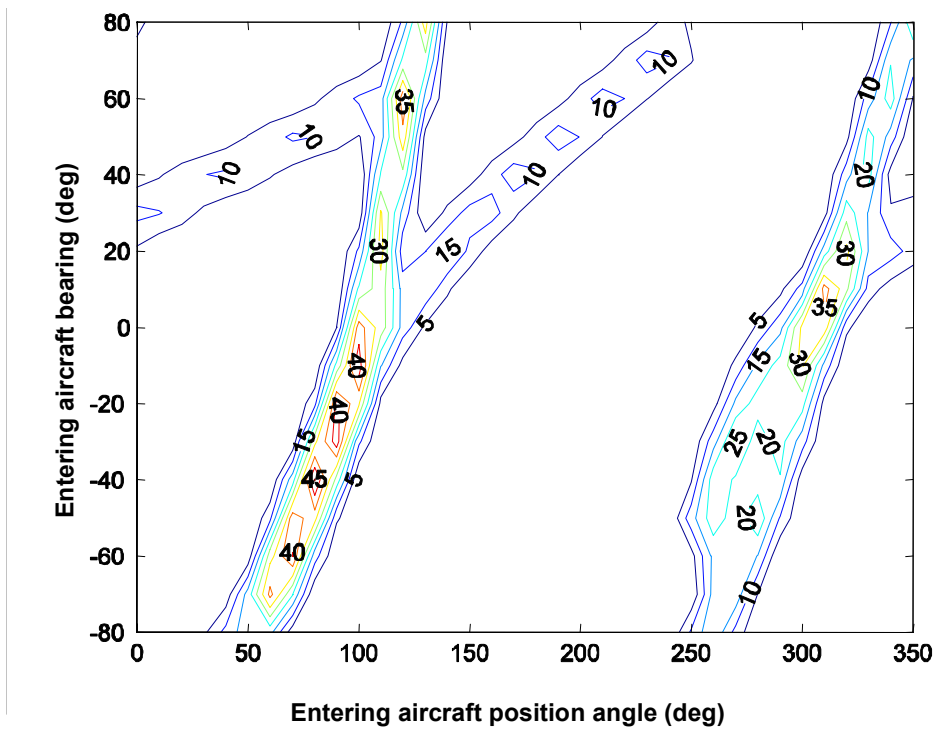


Figure 7. Complexity map for traffic situation 2, indicating contours of minimum control activity for all combinations of entering aircraft bearing and position angles

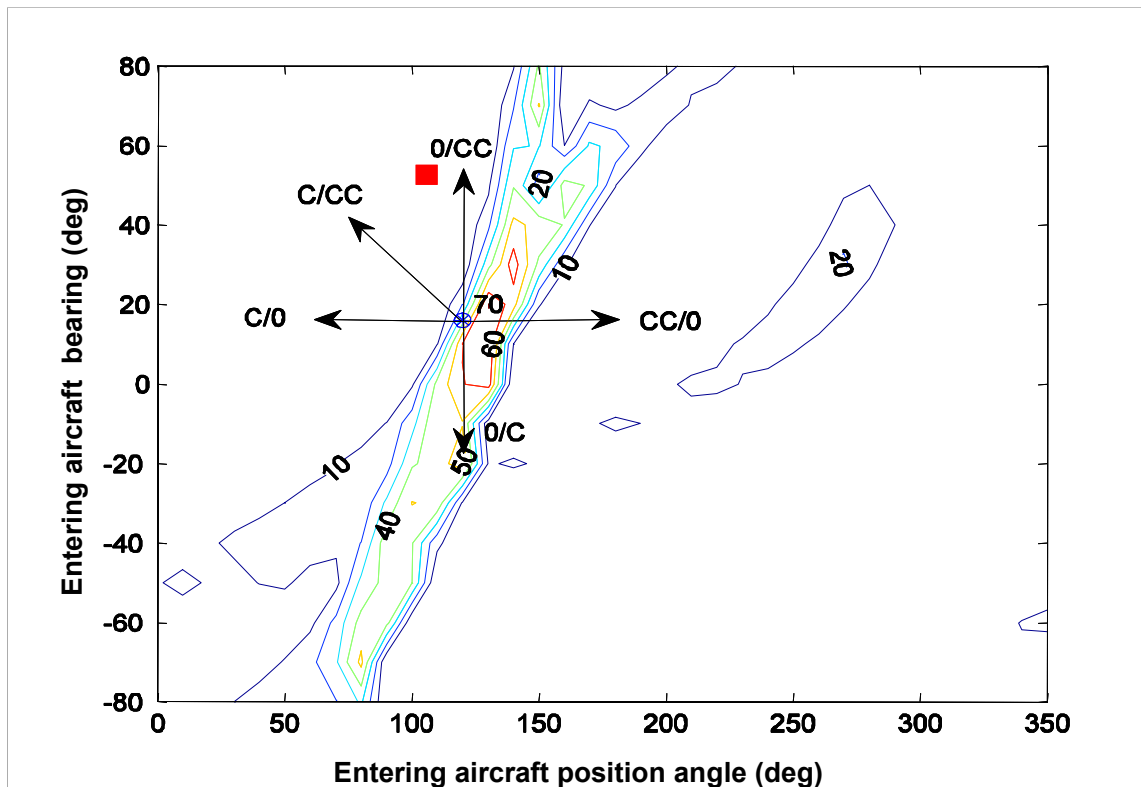


Figure 8. Control activity required for one entering aircraft into traffic situation 1

conflict free is the combination of increasing the entering aircraft's bearing and decreasing its position angle, shown by the vector C/CC.

(3) Where an entering aircraft's position angle and bearing correspond to concave regions of the complexity maps, neither positive nor negative changes in the entering aircraft's bearing can eliminate conflict without requiring other aircraft in the sector to also change heading.

(4) We can infer the impact of uncertain information. If real entry position of an entering aircraft is biased, denoted by red '■' in Figure 8, an increase in its bearing creates more conflict, contrasting with our discussion in (1) where an increase in its bearing was thought to be beneficial.

(5) Special attention is due to some parts of the sector boundary. For example, in Traffic Situation 1, the air traffic controllers should concentrate on the part of the sector boundary corresponding to entering aircraft with position angles between 75° and 175° , as aircraft entering in this area will require large control activity within the sector. Based on this kind of information, the airspace manager also can restrict traffic coming through this part of the sector boundary. This is one of the key capabilities for dynamic density operations [2].

Scalar measures of air traffic complexity

The complexity map provides detailed information about the control authority required within a sector to accept an entering aircraft. An advantage of this detailed information is the ability to quickly identify operationally relevant control activities, such as efficient changes in entering aircraft bearing or problematic entering points.

However, a scalar measure of complexity can also be derived when desired, by any of several methods. The "worst-case" value for required control activity may be used as an indication of the sector's sensitivity to inputs; by this measure, in the previous examples traffic situation 1 is more complex than traffic situation 2.

Alternatively, the area enclosed on a complexity map representing conditions requiring a control activity exceeding some minimum threshold may be calculated; in the previous examples, for a threshold of '0' traffic situation 2 will have a higher scalar complexity but for a threshold of '40', traffic situation 1 will have a higher scalar complexity.

Many other methods are of course, possible for reducing the complexity maps to scalar values, each with their relative merits.

Environmental changes

An additional capability of this formulation is to analyze how sector complexity is affected by environmental changes such as convective weather ‘shutting down’ a region within the airspace or, as examined in the following example, a partial closure of a sector’s boundary due to dynamic airspace management restrictions on the direction of traffic flow.

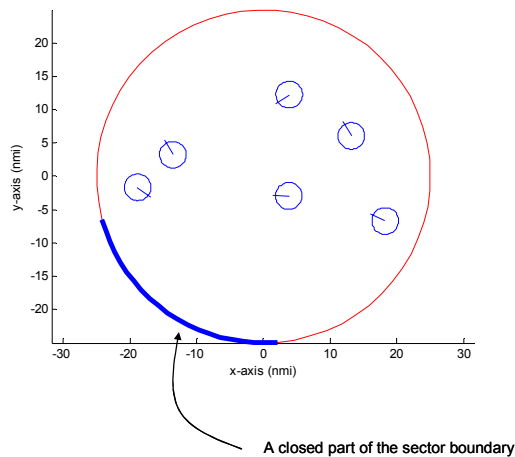


Figure 9. Environmental change: Partial closure of the sector boundary

Consider the traffic situation in Figure 9. Its corresponding complexity map is shown in Figure 10 for the nominal case where no sector boundary is closed. Now assume that a part of the sector boundary is closed as shown in Figure 9. As we can easily expect, air traffic complexity increases as shown in the complexity map given in Figure 11. While the range of conditions requiring any control activity does not change significantly between the complexity maps, the amount of control activity required within the affected space increases dramatically for a wide range of entering aircraft position angles and bearings.

Conclusion

In this paper, we demonstrated that air traffic complexity can be measured by the control activity required to maintain a conflict-free traffic situation when an aircraft enters into the sector. To achieve this measurement, we documented an input-output analysis formulation and proposed a complexity map that displays the state of the sector. The complexity map provides detailed insight into the control activity required to handle an entering aircraft, and the impact of environmental changes such as convective weather and partial sector boundary closures. We can also extract from the complexity map some scalar measure of air traffic complexity.

In addition, this method also can be applied to design problems. For example, based on the belief that there are intrinsically less complex air route structures, we are currently using this method to compare air route structures within sectors, assessing their complexity over a wide range of corresponding traffic conditions via Monte Carlo methods.

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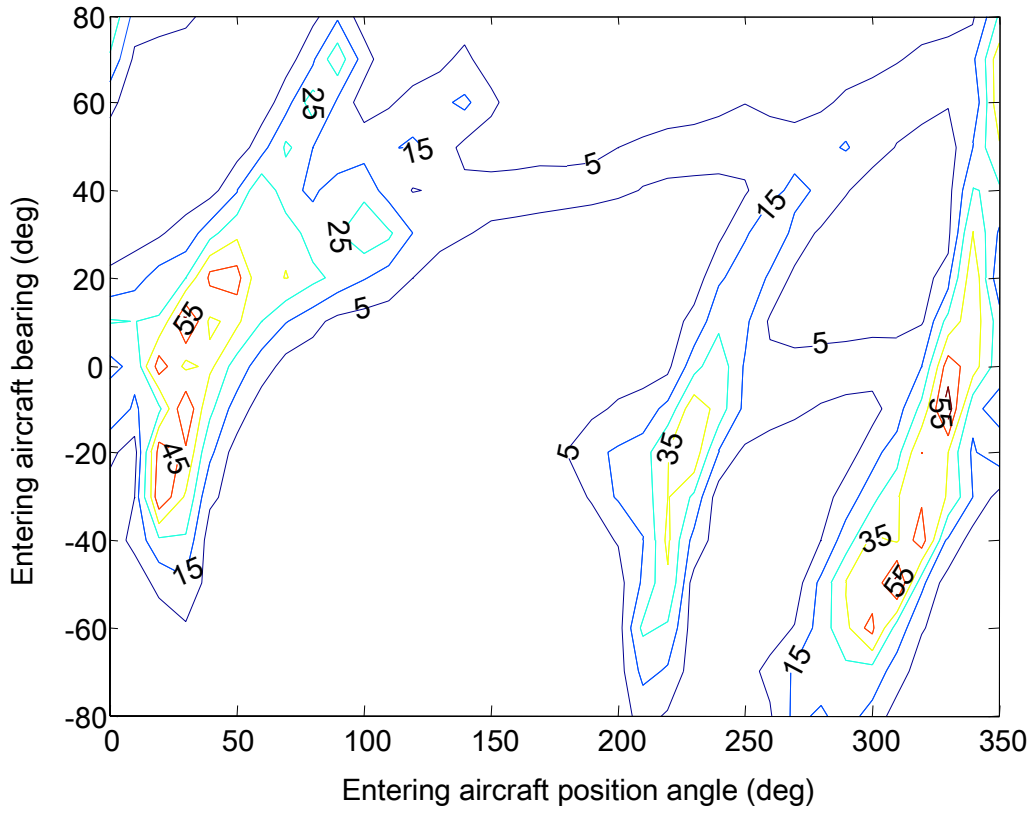


Figure 10. Complexity map: Sector with open boundary

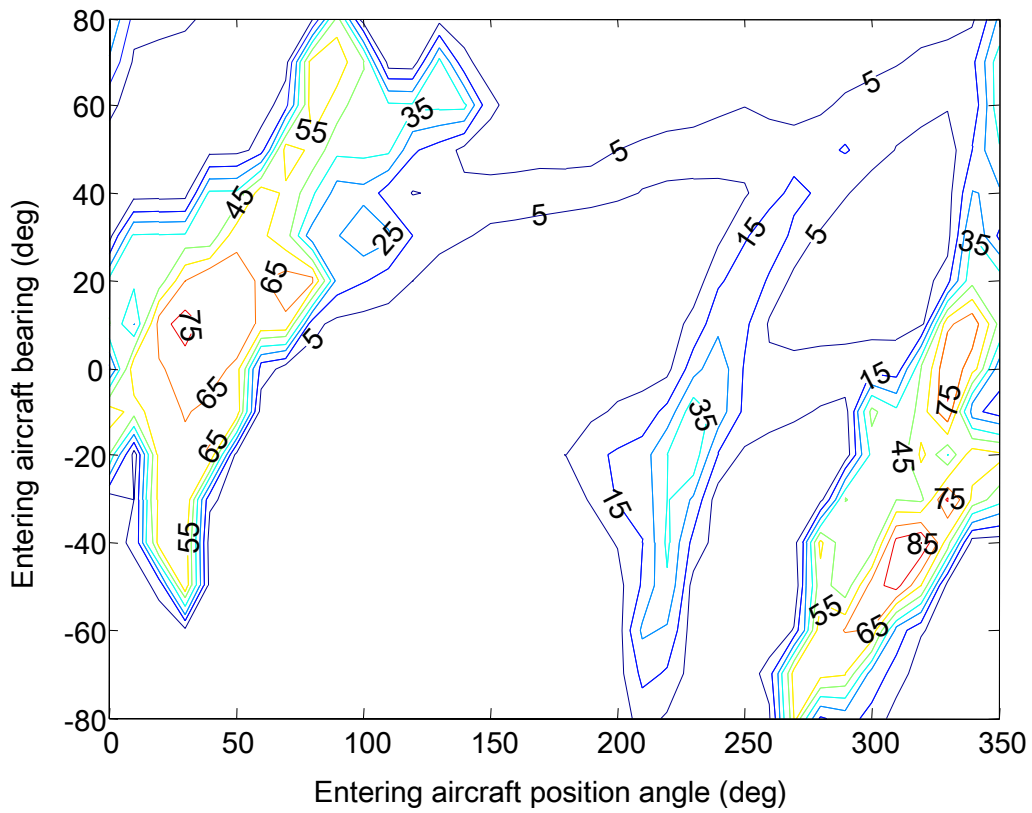


Figure 11. Complexity map: Sector with partially closed boundary

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