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Study on evolution characteristics of air traffic situation complexity based on complex network theory

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ABSTRACT

This study proposed a new method to describe air traffic situations based on the theory of complex networks and elaborate its evolutionary laws, expecting to reveal the basic characteristics of air traffic complexity. Based on 2D complexity and 3D complexity, a double-layer multistage dynamic network model was built and an air traffic complexity vector was proposed. The real flight data from four traffic control sectors were used to characterize statistically the evolution of air traffic situations. Results show that the complexity vector helps to describe the structural characteristics of air traffic situations and identify the evolutionary characteristics of different traffic situations. Based on k-means, air traffic situations were classified into three complexity patterns. The frequency of occurrence, life cycle, and transition probability of complexity patterns were statistically calculated. Results show that the traffic situations of high-altitude sectors bring more 2D complexity and less 3D complexity than those of low-altitude sectors. In most cases, the four sectors belong to medium complexity or below, and a specific complexity pattern appears in a certain period with a specific probability. The life cycle of air traffic complexity patterns is usually on the order of seconds or minutes and differs slightly among patterns. Transition probabilities of patterns indicate that the air traffic situation is evolving stably on the whole, but will probably runs into severe change.

1. Introduction

The basic task of an air traffic management (ATM) system is to guarantee the safety of air traffic. When two or more aircraft are approaching, controllers must promptly observe their proximity to each other, evaluate the potential risk of the air traffic situation, and provide corresponding solutions. Thus, quantitative analysis of the air traffic situation and description of the difficulty that controllers encounter in different traffic situations are important. Currently, the concept of air traffic complexity is usually used to describe the air traffic situation.

In the current air traffic control system, air traffic controllers provide services to airplanes and guarantee a safe flight. Thus, the difficulty controllers face in comprehending the air traffic situation is closely related to the assessment of their workload. The number of aircraft in a sector as the basic characteristic of air traffic is the basis for the study and assessment of controllers' workload and is the first well-accepted basic indicator of air traffic situation complexity [1–3]. Obviously, besides the number of aircraft in a sector, many other indicators are correlated with a controller's workload, such as airspace structure and traffic flow [1]. The airspace structure covers the physical structure of airspace, including terrain structure, number of air routes, and number of intersections. Traffic flow characteristics include the mix degree of aircraft types, proportion of climbing aircraft, proportion of descending aircraft, and proportion of clustering aircraft. These spatial structure and traffic flow factors jointly interact to form the overall air traffic complexity [4]. The complexity of air traffic systems has been intensively studied from the perspective of complex systems. Based on aircraft tracking information (e.g., location, velocity), the basic intrinsic characteristics of an air traffic situation (e.g., relative distance, relative velocity) can be computed. Therefore, the between-aircraft influence relationships can be mathematically described, and the complexity of a single aircraft pair can be computed. Then indicators such as fractal dimension and the Lyapunov exponent are used to describe the irregularity of between-aircraft influence relations, which serve as a measure of air traffic complexity [5]. Based on the aircraft approaching effect and conflict effect, two algorithms for computation of sector complexity were proposed by [6]. Regarding the impacts of abrupt disturbance on the between-aircraft relation in the original region, a complexity model based

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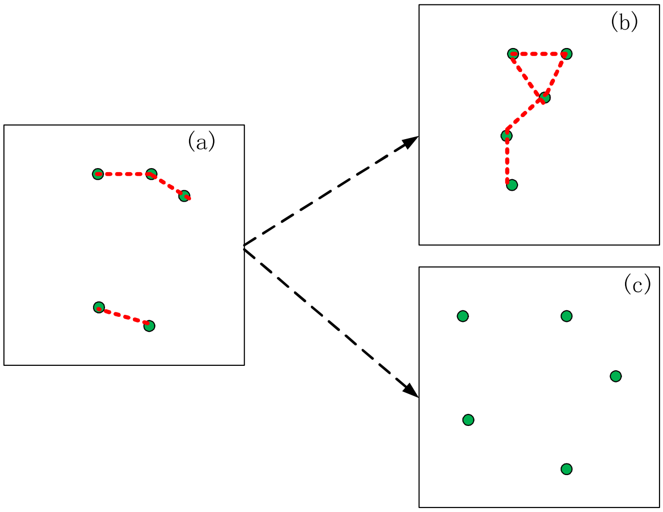

Fig. 1. Schematic diagram showing the evolution of air traffic situation.

on traffic flow disturbance was proposed, which defined the degree of complexity as a measure of control activities needed by a controller during emergencies [7–9]. Targeted at the characteristics of future air traffic control systems, some researchers have analyzed air traffic complexity on the basis of a trajectory-based operation [10–12]. Moreover, a dynamic model of the evolution of air traffic situations was built on the basis of between-aircraft influence relations; by describing the disorder of traffic organization as topological entropy, a novel standard for measurement of air traffic complexity was established [13,14].

The above studies focused on the complexity of air traffic situations from different perspectives, but ignored the between-aircraft proximity from the structural perspective. Histon proved that the traffic structure has a significant influence on the controller's cognitive complexity and suggested three ways to reduce the cognitive complexity from the perspective of structural simplification [15]. In fact, the structural characteristics of an air traffic situation are gradually evolving with time. Fig. 1 illustrates three air traffic situations with different network structures, with five aircraft under each situation. Specifically, the between-aircraft distances in Fig. 1(a) are very small and thus will interfere with the controller in resolving potential conflicts. The between-aircraft distances in Fig. 1(b) are smaller with some ring-like structures, which further prohibit the controller from formulating appropriate resolutions to conflicts. The between-aircraft distances in Fig. 1(c) are large, thus excluding any too-close proximity relation. Thus, despite the same air traffic density in the three situations in Fig. 1, the actual difficulties for the controller are varied, but such structural differences cannot be well reflected by the existing air traffic complexity indicators. Moreover, the traffic situation in Fig. 1(a) may evolve into the one in Fig. 1(b) or Fig. 1(c), and the evolved results will induce different control pressures. Thus, understanding the structural and evolutionary characteristics of air traffic situations will help in quantifying their degree of difficulty more accurately.

Numerous systems in nature can be described as networks. The concept of complex networks offers a method for abstraction and description of complex systems and highlights the topological characteristics of system structures. Generally, a system can be characterized by the complex network if the component units of the system can be abstracted into interrelations between units [16,17]. Many studies have applied complex networks to air traffic and divided them into macroscopic and microscopic types. From the macroscopic perspective, airspace units including airports and airway points are considered to be nodes, while the air traffic flow between nodes is regarded as edges. The evaluation of network robustness, connectivity, and other indices can provide guidance for airspace design and planning, and is focused on airspace structural characteristics [18–25]. From the microscopic perspective, aircraft are considered to be nodes, while the between-aircraft conflict or proximity relations are regarded as edges. This configuration helps in exploring traffic behavioral characteristics including flight conflict pattern and local congestion, providing assistance for air traffic control services, and is focused on traffic flow characteristics [26–28].

For a comprehensive analysis of evolutionary characteristics of air traffic situations, we divide the complexity into 2D complexity and 3D complexity and thereby build a double-layer multistage dynamic network model from the microscopic perspective. After the introduction of commonly-used network structure indicators, we put forward the concept of complexity vectors that can fully characterize the air traffic situation. In the classification of air traffic situations, we used the k-means algorithm to divide the corresponding complexity vector of a situation into three patterns. Finally, with routinely recorded radar data as the empirical basis, we statistically analyzed the main evolutionary characteristics of air traffic situations. Here we used the theories and methods of complex networks to statistically analyze air traffic situations and their evolution. In practical terms, better knowledge of air traffic situations and their evolution would allow traffic management coordinators to take strategic actions to prevent overloading of the tactical interventions and avoid unnecessary tactical maneuvers, thereby avoiding intolerable peaks in sector controllers' workload and raising sector capacity.

2. Modeling and data

2.1. Network model

A complex network is an abstraction of abundant real complex systems and thus reflects the various interactions and relations inside the complex systems. The basis of complex networks is the graph theory. Specifically, a network can be defined as a graph structure G composed of a node set and an edge set. Each node represents an individual in the real system, and each edge represents the interaction between two individuals.

During a flight, to reach their destination, aircraft follow trajectories that frequently intersect and overlap, especially in dense areas. The core task of ATM is to ensure that the between-aircraft separation does not violate the separation standard set by regulatory agencies. A flight conflict occurs when two aircraft are too close to each other, resulting in a loss of separation, which is a dangerous situation. Addressing aircraft conflict requires high-level cognitive activity and directly affects the air traffic system capacity. Thus, a flight conflict significantly affects the controller's workload and is the essence of traffic situation complexity [29–31].

An air traffic situation is essentially a time-variable complex system and thus can be abstracted and described from the perspective of complex networks. Here we denote aircraft as nodes, aircraft and aircraft conflict relationships as edges, and thereby, construct a network model to represent the air traffic operation situation. If at time t, the time until the predicted conflict is shorter than the preset threshold h (measured in minutes), and the vertical distance between aircraft i and j is shorter than the preset threshold v (measured in meters), then we define nodes i and j as connected via one edge. The network structure corresponding to time t, horizontal threshold h and vertical threshold v is expressed as $G_{h,v}(t)$. Admittedly, the corresponding network structure may be different depending on the thresholds. For the traffic situation at a given time point, if the threshold is too large, the number of connections will be increased, which reflects the traffic situation from the macroscopic perspective; if the threshold is too small, the