Investigating Air Traffic Control Dynamics Using Random Cellular Automata

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Abstract—We provide, in this work, a discrete model based on random cellular automata to express the air traffic dynamics and its complexity on the controlled airspace. The simulation identified the phase transition phenomenon and determined parameters having influence on the relation between local and global behavior of the system.

Index Terms—Air Traffic Control, Air Traffic Management, Complex System Modeling, Cellular Automata

I. INTRODUCTION

Air Traffic Management (ATM) can be modeled as a set of components of different subsystems in mutual interactions in order to accomplish the mission of simultaneously maintaining safety and sustaining growth. The ATM system is considered as a complex system because its behavior depends on a complex combination of various subsystems performing complicated functions. The evaluation of the impact of each function on the overall ATM system cannot be performed unless a specific approach is used. Understanding the mechanisms by which complexity may be reduced in the particular domain of ATM may provide important solutions to optimize the dynamics of the system and its structure.

Currently the air traffic complexity definition concerns especially the Air Traffic Control (ATC) subsystem and it depends on the airspace design and the traffic flow configuration. In 1998, Sridhar et al. showed that operational capacity of a sector depends on additional factors beyond the number of aircraft present in it [1]. Other researches have identified many factors that appear to influence the complexity of an air traffic situation but are not taken into account by the existing metrics. These factors include the distribution of aircraft in the sector, the shape of the sector, and the number of aircraft making vertical transitions.

The study of complexity in ATC has specifically focused on the identification of influent factors in an air traffic situation more or less complex. These factors are determined using basically two approaches:

- direct techniques using the results obtained by of verbal reports, questionnaires, and interviews.
- indirect techniques using statistical techniques analyzing controller judgments of the relative complexity of different air traffic situations.

Several metrics have been developed in response to the need for more objective and precise measures of complexity including sector size, sector shape, the configuration of airways, the location of airway intersections relative to sector boundaries, and the impact of restricted areas of airspace. A new air traffic complexity metric was introduced by Delahaye and Puechmorel in [2]. This metric is based on non-linear dynamical systems and expresses the complexity of an air traffic situation by identifying the organization of the aircraft trajectories and their clustering structure. It consists in computing the Lyapounov exponent corresponding to the non-linear dynamical system model that fits the real observations.

These complexity measures are very important to understand local behavior and dynamics of specific elements of the ATM system. However, these approaches lack of global view of the total dynamics of the system. Dynamics of air traffic can not easily be deduced from the local behavior of the ATM components. Thus, a top-down approach focusing on the properties and behavior of the whole system while integrating information provided by local studies will provide a better understanding of the underlying mechanisms in ATM complexity and efficient tools to optimize its functioning.

There are three interrelated approaches to the modern study of complex systems, (1) how interactions give rise to patterns of behavior, (2) understanding the ways of describing complex systems, and (3) the process of formation of complex systems through pattern formation and evolution (http://necsi.org/guide/study.html, 9/2006).

Our objective in this work is to understand the relationship between the local availability of the control sectors influence and the air traffic dynamics on the ATM network in order to understand how local situations (availability or unavailability of the components) influences the state of the whole system. Two basic aspects of the problem must be specified in order to perform a coherent modeling of the ATM behavior:

- proposing an adapted mathematical approach to model the ATM from a systemic point of view while integrating the local and heterogeneous interactions

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between the components.

- abstracting the capacity concept to the availability concept.

We provide a cellular automata (CA) based model integrating the local rules applied in a sector of the controlled airspace. It offers a holistic operational framework to test various hypotheses for flow management.

The paper is structured as follows: in section II, we present an overview of ATM complexity. Section II concerns a general presentation of the use of cellular automata to model complex phenomena. In section III and IV, respectively, we present our cellular automata based modeling of ATC and its simulation. We conclude, in section V, with a discussion of the results and future work.

II. ATM COMPLEXITY

Every organized human activity exhibits an opposition between two basic requirements: the division of labor into different tasks to be performed, and the coordination of these tasks to accomplish a mission. The complexity of the system is related to the efficiency of its structure and dynamics in accomplishing the global mission.

According to the New England Complex System Institute, complex systems *is a new field of science studying how parts of a system give rise to the collective behavior of the system, and how the system interacts with its environment.*


This definition can be used to describe ATM system and induces the fact that it should be studied using the mathematical techniques dealing with criticality and phase transition phenomena which are the main properties of complex systems and express the network effect phenomenon. The phase transition is an abrupt change in the behavior (or the state) of the system which occurs around a critical value of a key parameter called transition threshold.

The ATM system is a complex network composed of several heterogeneous and mutually interacting subsystems. The complexity of the ATM can be related to the following factors:

- System size
- Diversity of users
- Safety constraints
- Uncertainty (weather, human factor, technical factor...)

This complexity can be also related to the ATC subsystem representing the rigidly structured airspace and the largely centralized, human operated control hierarchy. For this reason, new approaches based on a more flexible organization of airspace are investigated by the aviation community. One of the interesting approaches is based on the concept of Free Flight defined by the Federal Aviation Administration (http://www.faa.gov/freeflight/) as a distributed system that allows pilots, whenever practical, to choose their own route and file a flight plan that follows the most efficient and economical route.

However this approach implies the use of precise algorithms to generate safe trajectories in order to maintain safe separation between aircrafts and to avoid the effect of hazardous weather. In [3], an *ant colony optimization based weather avoidance algorithm* is described. It generates optimal weather avoidance trajectories in Free Flight airspace. As in computer science, distributed systems are, for different applications, more powerful than centralized schemes. Our approach may provide a theoretical framework to compare the efficiency of different air navigation conceptions and to show if a distributed approach is better than a centralized one and in which conditions.

By considering the densely interconnected system of ATM as a network (that may be a hierarchical network) where components properties are heterogeneous and individual and by applying appropriate theories we are able to model the emergence of global properties in the system from the local behavior of its component (typically the availability and congestion of the airspace).

In this way we can take into account the coordination requirements representing the interactions between controllers in adjoining sectors, which is an important factor in ATC complexity [1]. It is also important to note that these interactions are closely dependent on the airspace design. In fact the topological structure of airspace defines the structure of the sectors coordination network. The space-time analysis that we propose in this research project is a general approach focusing on the intricate relation between these two fundamental aspects.

III. MODELING COMPLEX PHENOMENA USING CELLULAR AUTOMATA

In various natural and artificial contexts, we observe phenomena of great complexity. However, research in physics, biology and in other scientific fields showed that the elementary components of complex systems are quiet simple. It became crucial for scientific research dealing with complex systems to determine the mathematical mechanisms allowing including and understanding how a certain number of such elementary components, acting together, can produce the complex behaviors observed in these systems.

The second law of thermodynamics is an example of a general principle describing the global behavior of different kind of systems. It implies that the initial order is gradually degraded while a system evolves over time, so that at the end a state of maximum disorder (*i.e.* entropy) is reached. Many natural systems exhibit such a behavior. But there are also various systems having an opposite behavior; initial simplicity or disorder is transformed into great organized complexity.

Cellular automata studied by Stephen Wolfram represent an attempt to design the simplest mathematical model able to generate a great complexity. One of the most important current problems consists in finding general laws being able to be applied to study the majority of complex systems. A cellular automaton is in the simplest case one line made up of empty boxes. Each box carries one value 0 or 1. Thus, the system configurations are an ordered sequence of 0 and 1 evolving over time. At each time step, the value of each site is updated according to a specific rule. The rule depends on the value of a cell and that of its two closest neighbors.
According to Wolfram [4] CA are microscopic models for complex natural systems containing large numbers of simple identical components with local interactions. Even if the construction of the automats cellular is very simple, their behavior can be very complex. There are fundamental reasons showing that there is no general method which can universally be applied to predict the behavior of these systems. Compared with reality the cellular automata appear simplistic. However, they are currently considered as a fundamental tool in modeling and simulating complex phenomena, in particular concerning the auto-organized systems. The use of the cellular automats makes it possible to reduce the complexity of modeling to what is necessary to generate the phenomenon. It is a paradox of complex systems: the behavior of the system is unpredictable and complex (at a long term level) whereas the laws (or rules) which controlling it are simple and deterministic. Moreover cellular automata represent a powerful simulation tool. In fact a good simulation supposes computing power which can be obtained by a parallel computing. However, the local nature of interactions between cells makes the programming of cellular automata easy “to be paralleled”. The dynamic theory of systems was developed to describe the global properties of the solutions of the equations. Cellular automata can be regarded as a discrete representation of the partial derivative equations modeling the studied complex phenomenon.

We can distinguish the following categories of cellular automata:
- Homogeneous CA where rules are identical for all sites.
- Heterogeneous CA where rules may be different for different sites.
- Deterministic CA where rules are fixed functions.
- Probabilistic CA where rules are based on a certain degree of randomness.

Another interesting classification of CA, introduced by Wolfram, separates them into four classes according to the nature of their limiting behavior. This scheme is particularly interesting in complex systems studies, since it begins to identify the concept of complex behavior. Wolfram identified four classes:
- Class-one CA: evolve to a fixed homogeneous state
- Class-two CA: evolve to fixed inhomogeneous states or cycles
- Class-three CA: evolve to chaotic or aperiodic behavior
- Class-four CA: evolve to complex localized structures

This classification scheme has not yet found an analytical foundation but it is supported largely by observation of simulations of various CA.

For more detail on CA and its applications, we refer to [4.10]

IV. CELLULAR AUTOMATA BASED FOR ATC SIMULATION

A. The “physical model” of ATC

Air Traffic Control (ATC) is essential of ATM. In many countries, ATC services are provided throughout “controlled” airspace. The controlled airspace is subdivided into a number of sectors, each one is assigned to a team of controllers. The controller receive aircrafts into their sector, repeat to check the aircrafts trajectories for maintaining the separation between them, deviate the aircrafts to avoid the potential conflicts, and then transfer them to the next sector in their flight plan (in the plan of each flight, we can find a list of sectors which the aircraft cross through to joint two airports). These tasks induced workloads which due the limited capacity of sector. When a sector is “overloaded”, it can not receive aircrafts any more, and the aircrafts must be delayed for a certain time or be “re-routed”.

These local behaviors can be “optimal” locally, but they may also lead to a critical state of the whole system, where all sectors are unavailable. Analyze this phase transition can help us not only to avoid the bad situation but also to study the reliability of the system.

B. The CA based model for ATC

In fact, our model is based on a more generalized CA, which is closed to a simple agent based system. A portion of controlled airspace with a number of sectors is modeled as a CA, each sector corresponding to a cell. The transition rule is more sophisticated, as a result of certain local behavior of sector, which held by an agent.

We introduce here a new abstract notion of sector availability, instead of the notion sector capacity which depends on many factors and difficult to estimated. A sector has two states: it is available if aircrafts are still accepted into the sector. Otherwise it is unavailable.

Each automaton (agent) models the local behaviors of a sector as follows:
- Transferring/Receiving an aircraft: an aircraft entering in a sector \( s_a \) at the time \( t \) will be transferred to the next sector \( s_b \) in its flight plan:
  - At the moment \( t+\Delta t \) if \( s_b \) is available; where \( \Delta t \) is the means crossing time of the sector \( s_a \)
  - if \( s_b \) is not available at \( t+\Delta t \), aircraft can be delayed for 1 time unit, and transferred to \( s_b \) if \( s_b \) is available at the moment \( t+\Delta t+1 \)
  - Otherwise, aircraft must be rerouted to one of the common neighbor sectors of \( s_a \) and \( s_b \) (this sector should not be crossed by this flight) with a probability of \( p_1 \)
- An aircraft can be delayed for 1 time unit with a probability of \( p_2 \) (as the consequence of potential conflict resolution, bad weather, … for example)
- An aircraft can reduce the crossing time in a sector, if it was delayed, with a probability of \( p_3 \)

C. The implementation prototype of the model

Supposing to study a portion of en-route airspace, we model it as a 2D-lattice of size \( \text{spaceSizeX} \times \text{spaceSizeY} \). (Figure 1) each cell is a sector (\( \text{spaceSizeX} \) and \( \text{spaceSizeY} \) are the parameters of the simulator). The sectors can be in one of two states: available or unavailable. A sector \( S \) is available at a moment \( t \) if the number of aircrafts in this sector at \( t \) does not exceed its capacity \( C_S \), which is simply defined as the maximum number of aircrafts a sector can control simultaneously. The capacities of sectors in our implementation are distributed uniformly in \([\text{minCapacity}, \text{maxCapacity}]\).

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\begin{align*}
N_b &= 17000 \\
\text{Figure 3: Phase transition phenomenon observed when the threshold of parameter nbFlights is reached.}
\end{align*}
\]

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\text{Figure 4: The system absorbs local congestions when nbFlights is inferior the threshold}
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V. CONCLUSION AND FUTURE WORKS

In this paper, we presented a cellular automata based model which can help us to simulate the global behavior of ATC system, with many parameters. An implementation prototype is performed with Repast. With an artificial traffic pattern, the phase transition phenomenon is observed around a critical value of the number of flights parameter. The model is promising, and provides a holistic operational framework to test various hypotheses to study the reliability of system in controlled airspace.

For the future work, we aim to enrich the model with other local behaviors and plan to interpret it with the real data.

REFERENCES


