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A novel network approach to study communication activities of air traffic controllers

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ABSTRACT

Air traffic controllers play critical roles in the safety, efficiency, and capacity of air traffic management. However, there is inadequate knowledge of the dynamics of the controllers' activities, especially from a quantitative perspective. This paper presents a novel network approach to uncover hidden patterns of the controllers' behavior based on the voice communication data. We convert the time series of the controllers' communication activities, which contain flights' information, into a time-varying network and a static network, referred to as *temporal network* and *time-aggregated network*, respectively. These networks reflect the interaction between the controllers and the flights on a sector level, and allow us to leverage network techniques to yield new and insightful findings regarding regular patterns and unique characteristics of the controllers' communication activities. The proposed methodology is applied to three real-world datasets, and the resulting networks are closely examined and compared in terms of degree distribution, community structure, and motifs. This network approach introduces a "spatial" element to the conventional analysis of the controllers' communication events, by identifying connectivity and proximity among flights. It constitutes a major step towards the quantitative description of the controller-flight dynamics, which is not widely seen in the literature.

1. Introduction

The past decade has seen a significant improvement in the *air traffic management* (ATM) system in terms of safety, capacity, and efficiency. Great efforts have been made to enhance the performance of the ATM system, including the introduction of new operational concepts and protocols, deployment of advanced automation systems, and strategic research and development activities. Despite the ongoing exercise of new operational concepts and deployment of technologies in both Single European Sky ATM Research (SESAR) in Europe, and Next Generation Air Transportation System (NextGen) in the US, air traffic controllers are, and continue to be, playing critical roles in the ATM system. The in-depth understanding of the controllers' activities remains critical to ensure the safety and efficiency of the ATM system.

In many problems arising from human-driven complex systems, it is necessary to evaluate the operator's activities. Among various internal and external activities, mental workload has been the central focus of investigation in

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ATM-related research. Subjective measures, performance metrics, as well as psychophysiological indices, are often used to assess a particular type of cognitive load, which contributes to the workload (Galy et al., 2012). Along this line of research, earlier work was based on queuing theory and examination of controllers' routine work (Schmidt, 1978), while more recent approaches employ the controllers' subjective rating (Manning et al., 2002). In the attempt to prevent high workload, studies have focused on relevant factors that influence the workload. For example, many researchers have demonstrated that complexity factors can reduce sector capacity by increasing the controllers' workload (Loft et al., 2007; Laudeman et al., 1998; Sridhar et al., 1998; Averty et al., 2004; Hilburn, 2004). As the ATM system is undergoing a transformative development, there are ongoing attempts to analyze the controllers' activities in a futuristic operational environment. Human-in-the-loop studies have been conducted either to develop new cognitive metrics, or to evaluate decision support tools that incorporate future operational concepts (Li and Hansman, 2009; Kupfer et al., 2011; Guo et al., 2014). Issues that could arise while implementing key operational changes, such as trajectory-based operation and data communication, have been progressively identified (Lacher et al., 2011). Although there are extensive studies on controllers' workload and other topics related to human factors, the quantitative characterization and assessment of controllers' activities remain an open question and rarely studied. The limited knowledge about the underlying dynamics of air traffic controllers and the lack of appropriate mathematical tools have prevented us from an in-depth investigation of the controllers' activities. Conventional methods tend to target some specific problems, e.g. the analysis of controllers' workload in a given sector. With only a few exceptions (Clarke et al., 2011; Histon and Hansman, 2008), much less has been done to understand the dynamics of air traffic controllers' communication activities.

In the past few years there has been a surge of interest in both empirical studies of human activities and development of models to explain observed phenomena (Oliveira and Barabási, 2005; Barabási, 2005; Malmgren et al., 2009). Burgeoning empirical evidence regarding human dynamics recently uncovered similar patterns among human beings, which suggests that there exist universal mechanisms that govern human activities. Investigation of large empirical datasets of human activities, including mail correspondence (Oliveira and Barabási, 2005), email communication (Malmgren et al., 2008), text messaging, and online film rating (Zhou et al., 2008), indicates that the temporal patterns of human actions exhibit bursts of frequent actions separated by long periods of inactivity. Quantitative assessments on the circulation of bank notes (Brockmann et al., 2006) and mobile phone datasets (Gonzalez et al., 2008; Song et al., 2010) demonstrate that the human trajectories show a high degree of temporal and spatial regularities. Researchers have developed various models to reveal the fundamental rules that human follow when executing tasks.

We note that, in contrast to the activities examined in the aforementioned scenarios, people in safety–critical or mission-critical systems (e.g. air traffic management) are typically under pressure and stress. In ATM, any mistake made by the controller could cause huge economic costs or even loss of lives. Therefore, the understanding of air traffic controllers' behavioral dynamics is vital to the safety and efficiency of ATM systems.

Although controllers' activities are influenced by contextual factors such as airspace structure and air traffic flow distribution, cognitive analyses have uncovered several common strategies and techniques employed by controllers while handling traffic (Histon and Hansman, 2008). However, whether there is a similar mechanism behind their activities, which is the case for normal daily activities, remains unanswered, partially due to the lack of empirical data and proper analytical tools. Instead, most studies on relevant topics mainly rely on the assumption of *a priori* random distributions that the controllers' behavioral parameters follow, such as Poisson distribution, lognormal distribution, and Weibull distribution (Alam et al., 2013; Yang and Hu, 2010; Gravio et al., 2015; Prasad and Gaikwad, 2015).

Researchers from the fields of cognitive science and psychology have undertaken significant work in the attempt to analyze and understand, in a qualitative way, controllers' behavior, workload, and capacity. For example, Histon and Hansman (2008) report four strategies that air traffic controllers adapt in order to reduce the cognitive complexity: (1) standard flow; (2) critical points; (3) grouping; and (4) responsibility. However, no quantifiable outcomes regarding the controllers' behavioral dynamics are provided.

This paper aims to uncover the hidden patterns of controllers' behavior from their voice communication data, in a novel and quantitative way by leveraging network techniques. In particular, we propose a network approach to uncover the underlying mechanisms of controllers' activities and quantify the dynamics of the controller-flight interaction. Networks are widely used to represent the patterns of connections among various components of complex systems. Recently, there is hightened interest in the study of temporal networks, which fuse the temporal dimension into the classical network analyses (Chechik et al., 2008; Ahmed and Xing, 2009; Holme and Saramäki, 2011). For example, temporal networks have been applied to study the propagation of information in social networks (Liben-Nowell and Kleinberg, 2008; Rocha et al., 2010), and extract information from web posts to analyze prostitution activities (Rocha et al., 2010). Techniques are employed to convert time series to graphs, followed by network analyses, in order to unmask the hidden dynamics; see Zhang and Small (2006), Xu et al. (2008), Vassilis (2009), Haraguchi et al. (2009) and Gautreau et al. (2009). According to Donner et al. (2010), methods that convert time series to network structures can be classified into three categories:

(i) Mutual proximity of different segments of a time series. For example, in the recurrence plot approach, nodes are defined from the phase space trajectory and a link between two cycles when two nodes are rather similar (Marwan et al., 2009).
(ii) Convexity of successive observations (i.e. visibility graphs). Algorithm for converting time series into a graph can be found in (Lacasa et al., 2008).