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CONTROLLER-PILOT COMMUNICATION AS AN INDEX OF HUMAN PERFORMANCE IN THE NATIONAL AIRSPACE SYSTEM

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New capabilities to modernize the U.S. National Airspace System (NAS) include support of real-time information streams derived from many data sources across the NAS. This provision allows for system risk prognostics originating from sets of diagnostic health information. The current exploratory paper presents how to model human performance with the larger purpose of developing NAS risk prognostics. We explore ways in which human performance relates to communication and coordination among controllers and pilots in the context of their objectives, technologies, and environment. A literature review shows communication is often associated with controller performance in both experimental simulations and safety reviews. We gathered controller and pilot verbal communication data from two incidents and one accident and examined them using a dynamical systems method—discrete recurrence quantification analysis—to visualize and identify stability and flexibility between controller and pilot during the failures. From our findings, we conclude that controller-pilot need effective and timely interaction in order to overcome fatal incidents.

The U.S. National Airspace System (NAS) is a vast and complex system, comprised of macro and micro level components, such as airports, control centers, airlines, aircrafts, pilots, and passengers, that are nested within one another (Laskey, Xu, & Chen, 2012). According to the Federal Aviation Administration (FAA) report in 2018, more than 26 million flights carrying nearly 972 million passengers were operated in the NAS in 2017 (Meilus, 2018). In order to meet future growth rates of about 2% per year, advanced technologies, services, and procedures are being developed and implemented in the NAS under the Next Generation Air Transportation System program (Joint Planning and Development Office, 2010). With these capabilities, new and existing sources of real-time data will be available and provide opportunities for system-wide diagnostic health information and prognostic risk assessment via data fusion.

As an emergent property, safety of the NAS arises from interactions between many elements and different levels, ranging from those attributable to humans, technology, and the environment. NAS selectively open systems, each component needs to interact with other components, exchange resources and information, and operate under broad regulations to achieve overall system objectives (Harris & Stanton, 2010). Sometimes incidents and accidents result from insufficient interaction (communication and coordination) between humans (e.g., pilot-controller). The 2012 review by Edwards and colleagues centered on nine human factors constructs and reported that the leading contributors to incidents were communication, teamwork, and attention-related measures. In research of controller-pilot verbal communication, content-based evaluations have shown two consistent themes: (1) controller transmissions that are lengthy and (2) those with more than one piece of information correlate with more frequent pilot readback errors (Morrow, Lee, & Rodvold, 1993; Cardosi, 1996; Prinzo, Hendrix, &

Hendix, 2009). Controller-pilot communication often corresponds to phase of flight activity. Cardosi (1996) analyzed 48 hours of communication from eight Terminal Radar Approach Control (TRACON) facilities, 24 from high controller workload and 24 from moderate workload. Despite typical increases in pilot workload during departure and approach phases of flight, the authors found less than 1% of messages resulted in communication errors. Moon, Yoo, & Choi (2011) suggest that the level of air traffic density impacts verbal errors by controllers when operating terminal airspace sectors that service large Korean airports. The authors documented elements in controller-pilot verbal transmissions that indicated difficulties in interactions, such as “wrong call sign used” and “non-standard phraseology”. Results revealed controllers made 1.37 verbal errors when controlling 2-3 aircraft per 15 minutes, while 6.30 verbal errors were committed when controlling 30 aircraft per 15 minutes (Moon et al., 2011).

The content of communication will continue to provide value and support understanding with a multitude of team, individual, and data sets within air traffic research. In addition, another dimension to communication with a potentially rich source of understanding is everything but its explicit meaning. Cooke and Gorman (2009) describe methods of communication flow between teams (considered as a system) that have proven insightful. The first is a ratio of team members speech quantity, which can indicate the degree of influence one member has over others. Another is the communication required and passed score, or how much variation there is in actual team communication from expectations. Flow quantity represents how much speech each member of the team produces. In another study, Gorman, Amazeen, & Cooke (2010) underline the importance of coordination dynamics, and explain that “systems with different material substrates can exhibit the same dynamics”, which is known as dynamical similitude, which can be used to “guide selection of appropriate dynamical systems methods for a system that has not been previously analyzed using a dynamical approach” (Gorman et al., 2010, p. 285). Gorman et al. (2012) study applied discrete Recurrence Quantification Analysis (RQA) method on team communication flow data as a measurement technique for coordination dynamics Unnamed Vehicle (UAV) teams, wherein mixed teams (i.e., team members changed) or intact teams (i.e., stayed the same over successive experimental sessions. Interestingly, mixed teams were better able to adjust to unexpected perturbations, and this ability was linked to team level coordination dynamics. That is, mixed teams adopted a globally stable pattern of communication while exhibiting strong temporal dependence (Gorman, Cooke, Amazeen, & Fouse, 2012). Demir, Cooke, & Amazeen (2018) found that metastable team coordination (not too stable nor too flexible) between team members is important to successfully overcome novel events (i.e., team situation awareness) in a dynamic task environment. In the current study, we investigate the potential of dynamical systems perspectives to capture the differential dynamics of three cases between controller-pilot communication flow during incidents and accidents.

Aviation Incidents and Accidents

Three cases of controller-pilot audio transmissions were obtained from “Cockpit Voice Recorder Transcripts,” (2019), see Table 1, and analyzed via discrete RQA. The cases represent situations of particular interest, communication and coordination.

Table 1.
Flight Incidents and Accidents and Their Description

Flight	Description
Southwest Airlines Flight 1380 ("CVR Transcript Southwest 1380," 2018):	Boeing 737-700 enroute from New York–LaGuardia Airport to Dallas Love Field on April 17, 2018. Parts of the engine broke off and struck a window on the plane, causing rapid cabin depressurization and prompting the flight crew to conduct an emergency landing in Philadelphia International Airport. One passenger sitting adjacent to the failed window received fatal injuries and eight passengers received minor injuries. The aircraft sustained substantial damage.
US-Bangla Airlines Flight 211 ("US Bangla 211 CVR Transcript," 2018)	Bangladeshi airline (Bombardier 8-Q400) in Katmandu, Nepal in 2018. Airport tower cleared plane to land on runway 02, but confusing communication led the pilot to approach runway 20. Crashed due to runway confusion: 52 people died and 19 survived.
Aer Lingus Flight 12C ("CVR Transcript Aer Lingus 12C," 2018)	A flight from Dublin Airport to O'Hare International Airport in Chicago, Illinois. On takeoff, they reported a landing gear issue. They landed safely.

Discrete Recurrence Quantification Analysis Results

One of the approaches for investigating interaction patterns between the system components (in the controller-pilot case) and their change over time involves looking at communication flow using discrete Recurrence Plot (RP) and corresponding Recurrence Quantification Analysis (RQA) that quantifies how many recurrences with a given length are present by multidimensional space (phase space) trajectory in a dynamical system (Marwan, Carmen Romano, Thiel, & Kurths, 2007). The basis of discrete RQA is the RP (Eckmann, Kamphorst, & Ruelle, 1987) which is a visual tool for demonstrating a system's recurrent structure in the phase space when a system revisits specific states or sequences of states within a region of phase space over a period of time. In the case of two or more systems, discrete RP displays the times when two or more separate dynamical systems show a recurrence simultaneously (Marwan et al., 2007).

In this study, we used discrete RP to measure two or more behavioral dynamics of dyad communication flow encoded in discrete codes. The input to the discrete RP consisted of an ordered sequence of dichotomous codes: ‘‘0” for ‘‘ground/controller”, and ‘‘1” for ‘‘flight”, or if there was a third party involved "2" for "Rescue". Therefore, there is a series of discrete speaker states represented by a sequence of codes. Discrete RQA quantifies not only the effect of interventions (such as unexpected events) on instability, but also the dyad interaction processes and the dynamics that contribute to that process. The RQA was used to produce several measures, including: percent recurrence rate, percent determinism (DET), longest diagonal line, longest vertical line, entropy, and laminarity. Of these, the focal variable was determinism (DET; depicted in formula (1), Marwan et al., 2007), which indicates the amount of organization in the communication of a system. DET is derived from the recurrence plot by examining how the recurrent points are distributed: dyads with high determinism tend to repeat sequences of states many times—producing many diagonal lines (see Figure 1)—while controller-pilot with low determinism rarely repeat a sequence of states, producing few diagonal lines. The numerical value of DET comes from considering the upper triangle of points in the recurrence plot and then computing the proportion of points that form diagonal lines (see Figure 4) (Marwan et al., 2007).

$$DET = \frac{\sum_{l=l_{min}}^{N} lP(l)}{\sum_{l=1}^{N} lP(l)} \qquad (1)$$

where l is the diagonal line length considered when its value is ≥ $l$min and $P(l)$ is the probability distribution of line lengths. For instance, a 0% means that the time series never repeats; 100% means the time series repeats perfectly. DET essentially measures the degree to which two or more components (in this context ground and flight) are interacting in sync and how much they influence each other. This works by considering communication flow between controller and pilot, i.e., each dyad's communication for the duration of the task. For instance, in Figure 1a, we show discrete RPs between ground (i.e., controller) and flight (i.e., pilot) for SWA 1380 failure event. In the figure, the plot demonstrates a number of observations based on the dyads' (i.e. ground and flight) frequency of communication around a 17-minute events (79 communication sequences).

In Figure 1, we give three real case RPs based on ground and flight (and for Figure 1c also rescue) for two incidents and one accident (either two or three-code sequences) for (a) *Southwest Airlines Flight 1380 incident* (DET = 50%), (b) *US-Bangla Airlines Flight 211 accident* (DET = 64%), and (c) *Aer Lingus Flight 12C incident (*DET = 28%). These three examples of discrete recurrence plots demonstrate three different synergies among the ground and flight personnel during their own novel events. In Figure 1, the top of each RP depicts the communication flow between ground and flight (and the third party, if relevant; see Figure 1c: ground, Flight 12C, and rescue team). As a reminder, if ground sent a message, it was coded as 0, otherwise it was coded as 1 on the *y-axis* for the flight or it was coded as 2 for the rescue. The *x-axis* indicates the sequence of the communication flow (the number of communications sent).

According to Figure 1a, dyad communication shows metastable behavior (i.e. neither stable nor flexible: DET= 50%). In this specific case, air traffic control (ground) anticipated the issue in a timely manner and solved the issue regarding landing. The pilot and the controller were both aware of the situation. First, pilot pulled the nearest airport information from the controller, but quickly decided on Philadelphia. Then, the controller provided flight information to the Philadelphia airport in a timely manner. Even though loud sounds and other aircraft distractions caused initial communication issues between the controller and the pilot, as the aircraft stabilized, communications improved. In the middle of the event (Figure 1a), ground communicated and coordinated with the pilot (SWA 1380) and other aircrafts which were ready for landing. The controller's anticipation of the pilot's and airport's needs continued until the flight ended in a safe landing ("CVR Transcript Southwest 1380," 2018). This incident case shows the difference that timely awareness of the situation (aware of the technological failure by pilot and the controller), communication (timely anticipation between controller-pilot), and metastable coordination can make.

From the RPs, Ground-UBG 211 (see Figure 1b) had more synchrony than the other two cases. However, having more synchrony within ground and flight (i.e., controller-pilot) does not equate to successfully overcoming a novel situation; it can even create a novel situation based on the communication behavior. In this case, Ground-UBG 211 was one of the deadliest aviation disasters in aviation history and it was caused by confusion from conflicting communications between the controller and the pilot. In the beginning, the controller (i.e., ground) gave information to land on runway 02, but then the confusion about runway numbers start (between runways 02 and 20). Later on, the control tried to fix the confusion (see Figure 1b: between 30 to 40 black dots on the diagonal with repeated communication pattern). However, the confusion continued until the controllers gave a last try (long diagonal dot at the end of Figure 1b), and then the plane crashed ("US Bangla 211 CVR Transcript," 2018). The communication between controller and the pilot was full of confusion. Therefore, an argument can be made that the quality and effectiveness of the communication is more important than the quantity or frequency of communication. Most importantly, the controller and the pilot were not aware of the problem in a timely manner (i.e., lack of situation awareness).

Finally, in Figure 1c, three roles were considered to create the discrete RP and extract the DET measure. Overall, interactions in this incident were more flexible in comparison to other novel events, which may be partially explained by the mere presence of the third party (i.e., the third party increases the number of possible communication patterns: DET= 28%). When looking at the substance of the communication, the controller was coordinating and communicating with several flights and rescuers about the runways. In the beginning through the middle of the diagonal of the RP, the situation was routine in terms of landing and coordination was random across the three roles (*Ground, 12C, and Rescue*). Later, 12C noticed the landing gear issue and let the controller know in a timely manner. After that, both the controller and pilot anticipated each other's needs in order to land safely while rescue was preparing the runways ("CVR Transcript Aer Lingus 12C," n.d.). Overall, interaction dynamics and situation awareness indicate that effective interaction between the controller and pilot is crucial to effect situation awareness, successfully overcoming the failures.

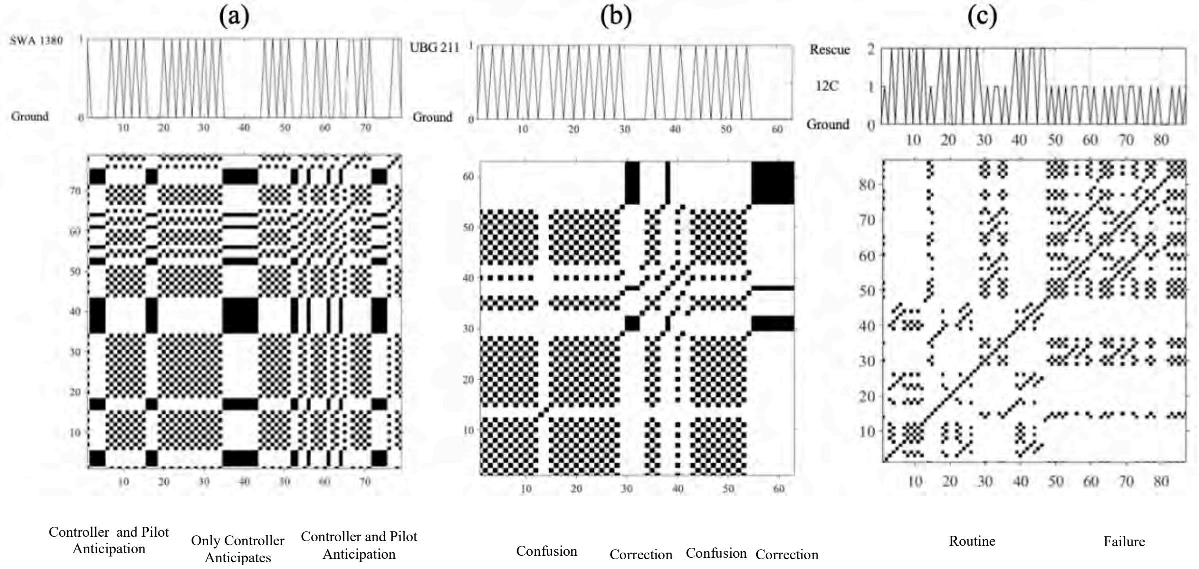

Figure 1. Discrete RPs based on number of communication events from: (a) Ground and SWA 1380 dyads (%DET= 50%), (b) Ground and UBG 211 (%DET= 64%), (c) Ground, Flight 12C, and Rescue (%DET= 28%).

Conclusion

We have presented three controller-pilot communication flows via discrete RP and RQA methods that differentiate three real cases based on discrete interaction sequences. The measures extracted from the RQA and visualizations of the interaction patterns show that effective communication and coordination is needed for effective situation awareness, i.e., overcoming the failures. Based on the previous studies (Demir et al., 2018), we expected the rigidity of the coordination dynamics between controller and pilot in the UBG 211 case would cause the fatal accident as well as lack of communication (confusion during the landing) and in turn lack of situation awareness. On the other hand, two other incidents demonstrated more flexible behavior across the roles (controller-pilot) to adapt to dynamic environment. In this case, the key lies in the dynamic transition between interaction and the environment. That is, controller-pilot are compelled to adjust their interaction patterns (flexibility) to adapt to changes in the environment and maintain a stable trajectory toward meeting their goals, such as safely landing. Thus, there are three crucial states for effective interaction in both temporal and spatial states “what needs to be communicated”, “when it needs to be coordinated”, and “how it needs to be communicated and coordinated”.

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