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DATA-DRIVEN SPATIOTEMPORAL SIMULATION OF GROUND MOVEMENTS OF AIRCRAFT FOR PREVENTIVE AIRPORT SAFETY

Pingbo Tang
Yanyu Wang
Zhe Sun

School of Sustainable Engineering and the Built Environment
Arizona State University
660 S. College Avenue
Tempe, AZ 85281, USA

Yongming Liu

School for Engineering of Matter, Transport, and Energy
Arizona State University
501 E Tyler Mall
Tempe, AZ 85287, USA

ABSTRACT

Comprehending how ground incidents and accidents arise and propagate during air traffic control is vital to both the efficiency and safety of air transportation systems. Historical data about airport operational events capture some processes about how improper collaboration among air traffic controllers and pilots result in incidents, accidents, and delays, but could hardly cover all possible air traffic control failures in various environmental conditions. The computational simulation could use historical data to identify repetitive aircraft movement behaviors and air traffic control processes shared in multiple air traffic control sessions and create stochastic models that represent the probabilities of the occurrence of certain aircrafts movements and control events under various contexts. This paper synthesizes four scenarios of aircraft operations around ramp areas during air traffic peak time for supporting the development of a quantitative spatiotemporal simulation that can help predict air traffic control risks based on historical data.

1 INTRODUCTION

As the air traffic volume increases dramatically in recent years, airports are increasingly facing capacity pressures (Liu et al. 2016). Airports in a metropolitan area with high complexity always generate an aircraft jam on the ground frequently (Sidiropoulos et al. 2017), which challenges the safety on the ground. From 1995 to 2008, approximately 429 commercial aircraft were involved in ground collisions (i.e., push-back, taxi, and so on), resulting in 973 fatalities (Wilke et al. 2014). The most crowded places in airports are ramp areas. The most useful method for reducing the collision between two aircraft is to instruct the pilots to keep sufficient safety clearances between their airplanes. Unfortunately, during the air traffic peak time, limited spaces in ramp areas could hardly ensure the safety clearance requirements specified in the instruction for pilots. Complex layouts of terminals and geometries of various aircraft models pose various scenarios of possible collisions. Historical database of airport operations hardly captures how complex geometries and motions of aircraft in various layouts of terminals result in incidents and accidents. As a result, the use of historical data for synthesizing principles of safe and efficient management of ramp areas of airports during air traffic peak time is mostly relying on subjective judgments and intuition of air traffic controllers and pilots.

More specifically, air traffic controllers and pilots have to utilize the limited spaces available at existing gates to guarantee safe and smooth airport ground operations. The size of each gate has been predetermined at the design stage. Airplanes parking in the ramp must fit into predefined ramp areas according to the regulation policy of the Federal Aviation Administration (FAA) (U. S. FAA. 1988). Driving with tight space constraints is challenging and damage-prone for large and expensive aircraft. In Los Angeles

International and San Francisco International airport where air traffic volume is enormous, aircraft are even towed into gates for avoiding deviation at the placement at gates (Smyth 2017). Figure 1 shows the crowded ramp area of Los Angeles International airport viewed in Google Earth. Newer models of aircraft (i.e., Boeing 777-X) tend to have larger dimensions than current models (Smyth 2017). Those large aircraft brought more challenges in the efficient moving of aircraft at ramp areas. In fact, in 2004 alone, a survey of Airport Council International (ACI) counted 3,233 incidents and accidents (922 with aircraft involved) at ramps of 193 airports worldwide (ACI. 2005).

Airport ground-collisions (i.e., runway incursion, taxiway incursion, ramp confliction, and so on) has been a research focus for a long time. Some studies established predictive models to help increase the situation awareness of pilots and air traffic controllers about pending collisions if no actions (S. D. Equipment 2010; Ludwig 2007; Jones et al. 2001). Some studies developed human behavior models to understand how pilots react when there a collision is pending if no actions (Chen et al. 2016; Kunzi 2012; Christodoulou and Kodaxakis 2006). On the other hand, some researchers proposed methods about taxi route improvements to help ground controllers aware of the risky routes and guide the pilot to reroute for take-off and landing (Messaoud 2017; Cafieri and Rey 2017; Hao et al. 2018).

One major limitation of past studies related to predictive models of ground collision avoidance in airports lies in the simplified geometric model of aircraft. Most studies viewed an airplane as a point while simulating the air traffic control and group operation processes. This simplified model can be useful when analyzing airplanes having vast separated distances (Qian et al. 2017). However, modeling aircraft as a point can hardly handle the situation where two airplanes are in proximity and crowded areas. The variation of the positions of airplanes can significantly influence the actual distance between two airplanes that are having large dimensions compared with the limited space in the ramp areas. For example, using the center points could get a distance between these two airplanes, but rotating these two airplanes could get a different actual surface distance between the wings of two airplanes. This fact indicates that the spatiotemporal details around ramp areas need quantitative spatiotemporal modeling and simulation to examine how collisions occurred and how to prevent collisions in crowded areas.

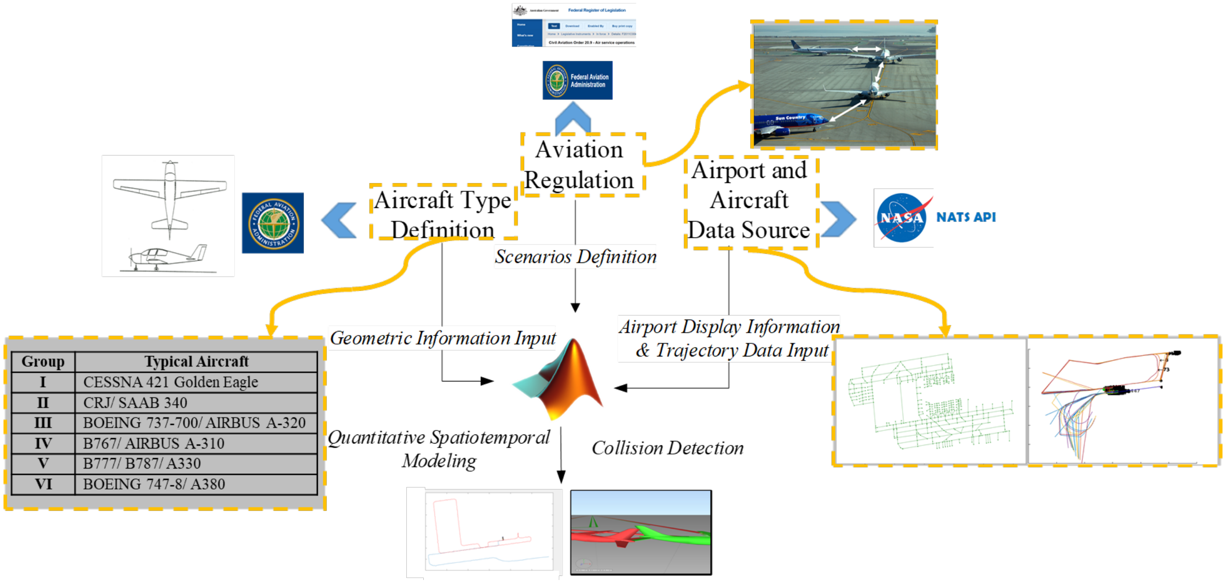
Figure 1: The Ramp Area of Los Angeles International Airport from Google Earth.

Aiming at supporting computational simulation that supports predictive ramp area management, this paper synthesizes four different collision scenarios with detailed representations of spatial conditions of aircraft and ramp areas based on historical data and literature review. Compared to a simplified model, detailed modeling of aircraft and geometric conditions of ramp spaces can represent detailed shapes of various aircraft models and the detailed geometries of ramp spaces available for aircraft operations. Random parameters within these quantitative models of collision processes and scenarios should be from historical data analysis for using these scenario models to predict probabilities of collisions based on historical data. *The main contribution of this paper is a formalization of the models of the four collision scenarios for establishing historical data-driven simulations of ramp area operations and collision risk control. The novelty of these new models compared with past computational simulation of airport operations is the capability of handling detailed geometric information of aircraft.* Future research will be on detailed historical airport operational data analysis to populate the values in those models.

2 METHODOLOGY

2.1 Overview of the Quantitative Spatiotemporal Modeling and Simulation Framework

In this paper, the authors established a quantitative spatiotemporal modeling and simulation framework that define typical scenarios of risky ground movements of airplanes to support predictive ground operation for achieving safety without compromising efficiency. Figure 2 shows an overview of this modeling and simulation framework. The quantitative spatiotemporal model in this framework represents four typical collision scenarios around ramp areas. The authors define these four scenarios based on extensive airport operational report analysis. The resources of airport operational reports include databases released by governmental agencies, social media, and other news outlets. A subsection below details the definitions and representations of these four typical collision scenarios.



Group	Typical Aircraft
I	CESSNA 421 Golden Eagle
II	CRJ/ SAAB 340
III	BOEING 737-700/ AIRBUS A-320
IV	B767/ AIRBUS A-310
V	B777/ B787/ A330
VI	BOEING 747-8/ A380

Figure 2: Methodology of Quantitative Spatiotemporal Modeling and Simulation.

Overall, each scenario defines three elements: 1) the aircraft models involved in the possible collision (Aircraft Type Definition), 2) the contextual aviation regulation practice (Aviation Regulation), and 3) airport operational information derived from airport design and historical data (Airport and Aircraft Data Source). The first two elements are predefined models or knowledge representations what are usually general knowledge that would not change from one incident/accident to another. The third element is specific data that capture specific details of individual incidents or accidents. Statistical analysis of these historical data of airport operation can produce the random distributions of the parameters involved in the models defined in the first two elements. Such random distributions form the basis of computational simulations that predict vulnerable parts of the airport design or dangerous parts of the ramp operational processes. For example, statistical analysis of ramp area operational processes could reveal the frequencies of certain types of aircraft deviating from a specific type of as-planned taxing paths in certain types of ramp area layouts. That frequency can help produce a random number that represents the probability of trajectory deviations of that type of aircraft under certain contextual conditions (e.g., taxing paths, airport layout, and time of the day). Such type of statistical information can support simulation models to generate random numbers based on historical data that capture the probabilities of certain behaviors of aircraft.

In this research, the authors use MATLAB as the platform to develop computational simulations based on these scenario representations and historical data collected from various databases maintained by different agencies, such as NASA. For each collision scenario, the authors use a quantitative spatiotemporal modeling approach to represent the geometric information of the aircraft accurately. The aircraft modeling should also consider other constraints such as turning angle, designed brake stopping distance and other move constraints due to its character. Combined with 4D visualization and clash detection software tools such as Navisworks (Autodesk Naviswork, 2019), this MATLAB-based approach can illustrate the movements of aircraft in 3D digital representations on the computer screen and highlight proximity or collision cases between airplanes. Navisworks software allows definitions of "clash tolerances" that represent the safety clearances between airplanes – any airplanes stay closer than a predefined safety clearance will become red in the visualization environment of Navisworks. The authors can define different safety clearances for different scenarios based on the regulation standards for airport operations. For specific aircraft models, the regulation standards specify the minimum distances between two airplanes for safe operations.

2.2 Airplane Categories Defined in the Four Scenarios

FAA's Airplane Design Group defined the airplane categories, as shown in Table 1. The geometric information listed in the table supports the development of detailed 3D models of aircraft involved in the four scenarios of possible collisions in ramp areas. The authors used commercially available design software tools to create such 3D models of aircraft and then import those 3D models into the simulation platform based on MATLAB and Navisworks for the simulation of different types of collisions.

Table 1: Airplane categories defined by the Airplane Design Group.

Group	Wingspan in feet (m)	Tail Height in feet (m)	Typical Aircraft
Ⅰ	< 49′ (15m)	< 20′ (6.1m)	CESSNA 421 Golden Eagle/ PIPER PA–31
Ⅱ	49′ (15m) - < 79′ (24m)	20′ (6.1m) - < 30′ (9.1m)	CRJ/ SAAB 340
Ⅲ	79′ (24m) - < 118′ (36m)	30′ (9.1m) - < 45′ (13.7m)	BOEING 737-700/ AIRBUS A-320/ EMBRAER ERJ 190-100
Ⅳ	118′ (36m) - < 171′ (52m)	45′ (13.7m) - < 60′ (18.3m)	B767/ AIRBUS A-310
Ⅴ	171′ (52m) - < 214′ (65m)	60′ (18.3m) - < 66′ (20.1m)	B777/ B787/ A330
Ⅵ	214′ (65m) - < 262′ (80m)	66′ (20.1m) - < 80′ (24.4m)	BOEING 747-8/ A380

2.3 Typical Collision Scenarios

A review of recent thirty safety reports in the Aviation Safety Report System (ASRS) revealed that four typical scenarios represent all recorded ways that lead to collisions around ramp areas. Figure 3 illustrates four typical collision scenarios in ramp areas. Figure 4 shows the percentages of accidents caused by these four scenarios according to the review of 30 accident reports in ASRS. The following paragraphs define these four types of scenarios in detail.

Scenarios 1, 2, and 3 are related to moving aircraft, while scenario 4 represents one standing aircraft with one moving aircraft. Scenario 1 illustrates that an airplane in the red frame is moving to its gate, while the airplane in the yellow frame is taxing towards it. Scenario 2 illustrates that the airplane in the red frame is pushing back from the gate, while the airplane in the yellow frame is taxing behind it. Scenario 3 illustrates that the airplane in the red frame is pushing back from the gate, while the airplane in the yellow frame is taxing towards it. Scenario 4 illustrates that the airplane in the red frame is standing at the gate with a little deviation from its designed place, while the airplane in the yellow frame is taxing behind it.

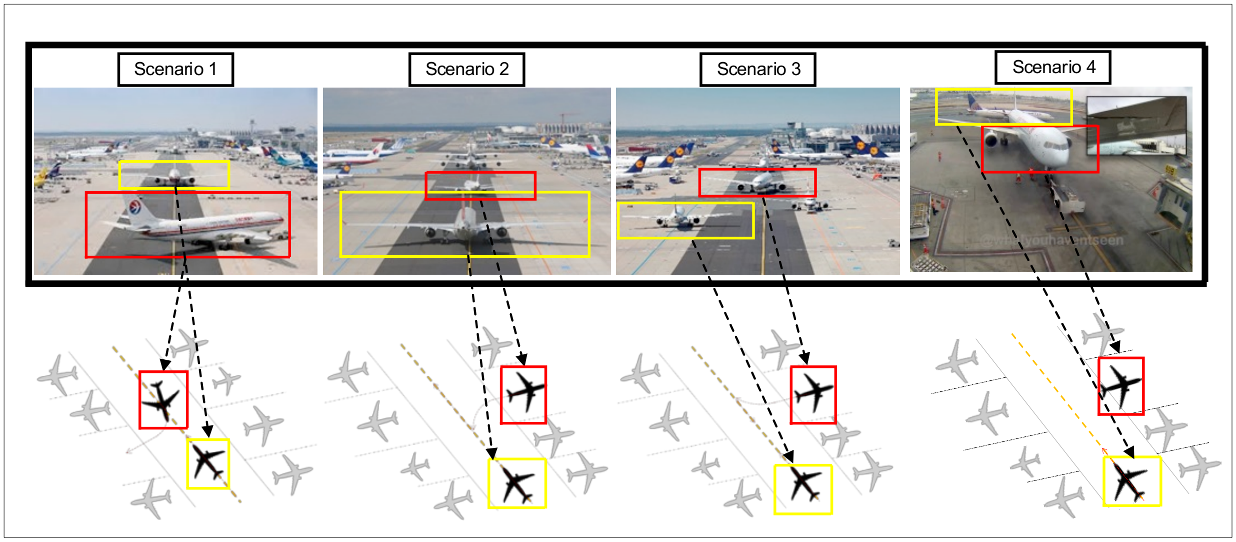


Figure 3: Four different type of scenarios of potential collisions in the stand area.

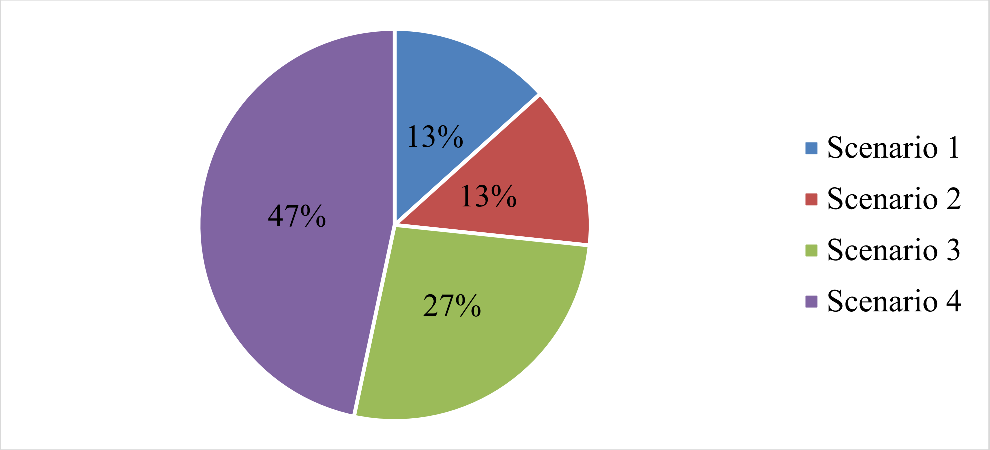


Figure 4: Percentages of four different types of scenarios of ramp area collisions according to the review of 30 accident reports in ASRS.

3 QUANTITATIVE SPATIOTEMPORAL MODEL

The workflow of using the developed quantitative spatiotemporal model for computational simulations contains two major part, as shown in Figure 4. The first part is data pre-processing, and the second part is the computational simulation of the four typical collision scenarios with changes of speeds and other relevant parameters under the control of the pilot or air traffic controllers (e.g., changing paths deviating from the as-planned taxing paths). With the collisions generated based on computational simulation and clash visualization in Navisworks, the authors can export the total number of collisions and occurrence times of those collisions.

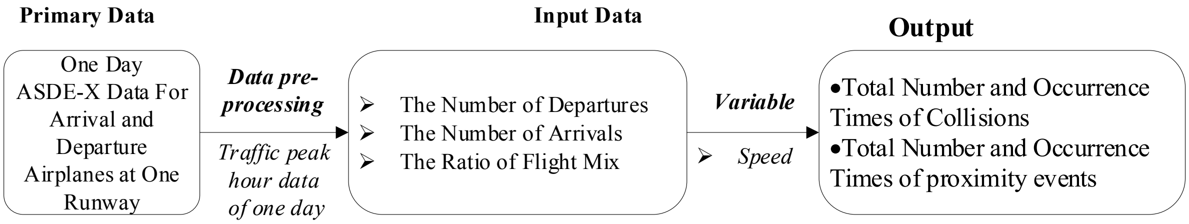


Figure 4: Workflow of Quantitative Spatiotemporal Model.

Another type of outputs of this modeling and simulation framework are proximity events – these events indicate that two airplanes are not clashing, but the distance between them is smaller than a predefined safety clearance. Proximity events all have occurrence times associated with those events. The total number of proximity events and the densities of proximity events in certain areas could be precursors of incidents or accidents, as those are numbers indicating how crowded certain ramp areas are. Total numbers and densities of proximity events across an airport, therefore, could serve as a "heat map" to visualize risk levels of collisions between airplanes. The following paragraphs provide more details about the technical process of data preprocessing and computational simulation, while the following section (section 4) presents a heat map that visualizes the densities of proximity events in Los Angeles International Airport based on two hours of data around a collision in 2017.

This paragraph presents the details of the data preprocessing procedure. Using one-day data of ASDE-X in a particular airport, an instance of one hour was generated to represent the traffic peak time of departure and arrival situation in one day. The authors used the ASDE-X data of Los Angeles International Airport (LAX) on September 12, 2017. In this stage, the authors found one hour that has the highest departure and arrival rates of airplanes within that day and set that one hour as the traffic peak time. For simulation, the authors considered simulating three (3) input parameters and one (1) variable. The three input parameters were: 1) The number of departures; 2) The number of arrivals; and 3) The ratio of aircraft mix. The one variable is the ground moving speed of each aircraft. The authors input the historical flight numbers of departures and arrivals into the simulation model to track the status of airplanes. As for aircraft mix, the authors count the number of each type of aircraft and using the ratio of all aircraft to represent aircraft mix.

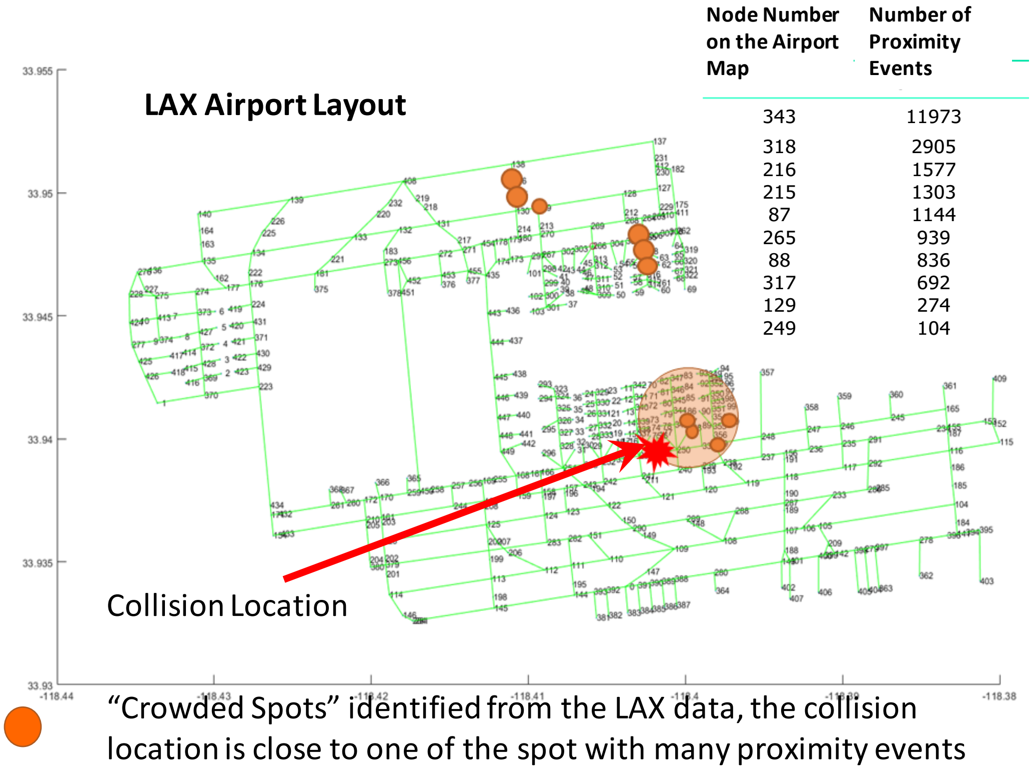
This paragraph presents the computational simulation process for predicting collisions or proximity events based on operational parameters of aircraft on the ground. In this study, the authors varied the variables (speeds of aircraft involved in the scenario simulated) and observed the occurrences of collisions and proximity events. The aircraft usually have a pre-determined taxi time and path (Bosson et al. 2015), but some airplanes could deviate from those predefined time due to some uncertainties, such as wind speed. Hence, focusing on varying speed for all four scenarios is reasonable. Some literature (Guépet et al. 2017) guided the authors to use a maximal speed of 5 m/s for the taxiways around the ramp area. The speed of aircraft will obey the Gaussian distribution with the mean and variance of the Gaussian distribution derived from historical speed data collected in past airport operations.

The following section presents results for evaluating the effectiveness of the proposed spatiotemporal simulation framework in predicting collisions and proximity events. In other words, the authors evaluated the reliability of the computational modeling and simulation framework by comparing the outputs of the simulation results and the actual operational data. When the numbers and spatial distributions of collisions and proximity events across an airport align well with the simulation, then the simulation model captures the mechanisms and random properties of airport operations for reliable collision prediction.

4 RESULTS

This section presents the results of the development of the simulation model and the testing results of the simulation model. For the development of the simulation model, the authors conducted statistical analyses of historical data collected by Airport Surface Detection Equipment, Model X (ASDE-X) platform. Spatiotemporal distribution analysis of two-hours of ASDE-X data collected before and after a collision in 2017 at a ramp area of the Los Angeles International Airport (LAX) – one hour before and one hour after that collision for the data collection. Figure 5 below shows the spatial distribution of the proximity event across LAX. Such historical data analysis results will be useful for defining random parameters in the computational simulation model for simulating how collisions occur and influence ground operations.

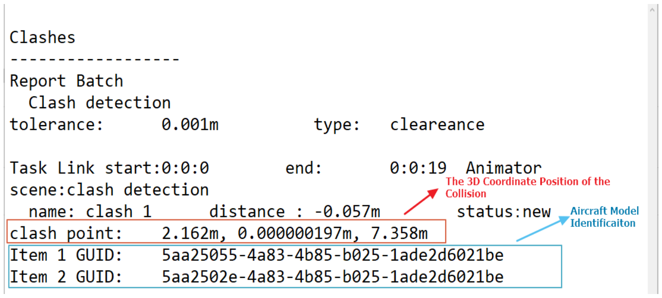
For testing the simulation model, the authors have tested Scenario 1 with two airplanes of model A380 in Navisworks. Using the quantitative spatiotemporal model, the Navisworks can generate the collision report, as shown in Figure 6. The authors found that more detailed geometric models of aircraft can help more accurate detection of collisions. More specifically, for the LAX collision studied in this research, the authors found that the closest distance between the two airplanes involved in the collision is 60 meters, which is larger than the 50-meter safety clearance specified in the FAA regulation. Such findings indicate that large airplanes could still collide with each other if the regulation standard did not adequately consider the detailed geometries of the aircraft. More detailed studies are still on-going for assessing the impacts of detailed geometric models of aircraft on the reliability of collision and proximity event prediction.



Node Number on the Airport Map	Number of Proximity Events
343	11973
318	2905
216	1577
215	1303
87	1144
265	939
88	836
317	692
129	274
249	104

● "Crowded Spots" identified from the LAX data, the collision location is close to one of the spot with many proximity events

Figure 5: Spatial distribution of proximity events around nodes of the internal transportation network of the Los Angeles International Airport: the location of the collision occurring in the middle of the two hours of data collection is one of the location where the proximity events were dense.



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Clashes
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Report Batch
  Clash detection
tolerance:      0.001m          type:   cleareance

Task Link start:0:0:0       end:       0:0:19  Animator
scene:clash detection
  name: clash 1      distance : -0.057m        status:new
clash point:    2.162m, 0.000000197m, 7.358m
Item 1 GUID:    5aa25055-4a83-4b85-b025-1ade2d6021be
Item 2 GUID:    5aa2502e-4a83-4b85-b025-1ade2d6021be
```

Figure 6: One Time Simulation Collision Report.

5 CONCLUSION

This paper presents a spatiotemporal modeling and simulation framework of airport ground operations for a more reliable prediction of collisions and proximity events around ramp areas during air traffic peak time. The main focus is to use historical data and reports to synthesize four scenarios of collisions that involve different types of collisions involving aircraft of different sizes, with proper consideration of the detailed geometries of aircraft. The results indicate that the statistical analysis of airport ground operation historical data is a basis for developing stochastic simulation models of airport operations. More specifically, current results show that the proximity event captured in historical data has a high concentration at the location of a collision. That alignment of collision and proximity event concentration locations reflect the feasibility of using proximity event density for guiding the definition of random parameters that determine the probability of collisions. The authors also tested the developed simulation method using one scenario and were able to output collision time and location that align well with the actual collision.

Future research will further develop the modeling and simulation framework along the following directions:

1) Complete more simulation for all four scenarios defined in this paper;
2) Conduct more statistical analysis about the spatiotemporal distributions of proximity events and use those statistical analysis results to define random parameters related to spatiotemporal conflicts between aircraft movements on the ground;
3) Examine more detailed geometric representations of aircraft for understanding how detailed geometric information influence the reliability of collision prediction produced by the simulation.

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AUTHOR BIOGRAPHIES

PINGBO TANG is an Associate Professor in the School of Sustainable Engineering and the Built Environment at Arizona State University. He holds a Ph.D. in Civil and Environmental Engineering from Carnegie Mellon University. Dr. Tang's research explores imaging (e.g., LiDAR) and information modeling techniques (e.g., Building Information Modeling) to support visual data-driven management of construction sites, constructed facilities, and civil infrastructure systems. He won one of the best paper awards of ASCE Construction Research Congress 2009 and the 2013 Recent Alumnus Achievement Award of Carnegie Mellon University. He is a recipient of the National Science Foundation Early Faculty Career Award from the Civil Infrastructure Systems (CIS) program in 2015. His email address is tangpingbo@asu.edu.

YANYU WANG is a Ph.D. student major in Construction Management in the School of Sustainable Engineering and the Built Environment at Arizona State University. She holds Masters' Degree in Construction Management from the College of Civil Engineering and Mechanics of Huazhong University of Science and Technology. Her e-mail address is ynwang@asu.edu.

ZHE SUN is a Ph.D. student major in Construction Engineering in the School of Sustainable Engineering and the Built Environment at Arizona State University. He holds Masters' Degree in Civil and Environmental Engineering and Industrial and System Engineering from the State University of New York, University at Buffalo. His e-mail address is zsun43@asu.edu.

YONGMING LIU is a professor in the School of Engineering of Matters, Transport, and Energy at Arizona State University. His research interests include fatigue and fracture analysis of metals and composite materials, probabilistic methods, computational mechanics, and risk management. He completed his Ph.D. at Vanderbilt University and obtained his Bachelors' and Masters' degrees from Tongji University in China. Dr. Liu is a member of AIAA, ASME, and ASCE and serves on several technical committees on probabilistic methods and advanced materials. His email address is Yongming.Liu@asu.edu.