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Metamodel-based direction guidance system optimization for improving efficiency of aircraft emergency evacuation

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ABSTRACT

It is a very common phenomenon that airline passengers always instinctively choose the nearest exit to evacuate in emergency situations. However, such a decision may not be the wisest choice as airline passengers oftentimes lack awareness of aircraft configurations and evacuation capacity of each available exit. To improve the efficiency of aircraft emergency evacuation, a direction guidance system that guides passengers to escape from the optimal exits is proposed. Determining the optimal evacuation directions via the evacuation simulation model developed in our earlier work can essentially be viewed as an optimization problem. The kriging model, acting as a metamodel, is utilized to alleviate computational burden of running the simulation model and approximate the underlying relationship between inputs (evacuation signs) and outputs (evacuation time). To improve the accuracy of the kriging model at the region of interest, a sequential sampling strategy is used to add extra samples as a complement to the initial sample set to tune the initial kriging model. The decision validation metrics along with a termination criterion are used to validate the globally optimal solution with a certain degree of confidence. As demonstrated in the case studies, the proposed metamodel-based optimization method is computationally efficient and the evacuation time can be significantly saved.

1. Introduction

As reported by both Airbus and Boeing companies, a new generation of civil aircrafts is designed with larger capacity in mind, carrying up to more than 1000 passengers (Australian Business Traveller, New Tech Spy). Consequently, the safety of newly designed aircrafts becomes a great concern from the perspective of both manufacturers and passengers. The investigations from the National Transportation Safety Board (NTSB) reveal that 78% of all fatalities occurred post-impact, of which 95.4% resulted from smoke inhalation and burns due to slow and inefficient evacuations (CAAPS, 1999). If post-impact crash survivors can be evacuated promptly, the survival rate would increase by 98.3% as claimed by NTSB (CAAPS, 1999). From this point of view, to ensure safe and efficient evacuation of passengers from an aircraft in the event of survivable crash is of great importance. The International Civil Aviation Organization (ICAO) requires that aircraft shall be equipped with sufficient emergency exits to allow maximum opportunity for cabin evacuation within an appropriate time period (International Civil Aviation Organization, 2010). More specifically, FAA certification criteria and test methods are integral to evaluating the evacuation capability of a new aircraft through its "90-s rule". This rule requires that all passengers and crew must evacuate from the cabin of an aircraft to the ground under simulated emergency conditions within 90 s, with only a half of emergency exits available (FAR Part 25, 1999). Every newly released civil aircraft is forced to conduct a suite of tests to ensure that emergency evacuation requirements are fully met before aircrafts get service permission.

However, conducting a real aircraft evacuation trial is oftentimes unaffordable since it is extremely expensive and may cause severe injury to participants, especially for testing in large civil aircrafts (Liu, Wang, Huang, Li, & Yang, 2014). To overcome these issues, computer simulation models, like airEXODUS (Galea, 2006; Galea, Blake, & Lawrence, 2002), have been developed in recent years to emulate the evacuation process of real evacuation trials. The advantages of simulation models include not only reducing expenditure and avoiding potential risks in real evacuation trials, but also providing manufacturers very useful insights

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on the evacuation performance of a new aircraft before the aircraft is physically built and/or put into service. Nevertheless, results of the simulated aircraft emergency evacuation process heavily rely on the accuracy and credibility of simulation models. Many attempts have been made to improve evacuation simulation models by emulating evacuation behaviors of passengers in a more realistic and accurate way. For example, Galea, Wang, Togher, Jia, and Lawrence (2007) considered the impact of aircraft post-crash fire in their evacuation simulation model. Kirchner, Klüpfel, Nishinari, Schadschneider, and Schreckenberg (2003) took account of the competitive behaviors of individual evacuees in aircraft emergency evacuation. Miyoshi, Nakayasu, Ueno, and Patterson (2012) developed an evacuation model considering the influence of panicked passengers. Most recently, we developed a new evacuation simulation model that is capable of considering variations of passengers' physical characteristics, e.g., waist size, gender, age, and disabilities. A multi-level fine network representation together with a new evacuation route selection strategy was used to enhance the accuracy and credibility of the simulation model (Liu et al., 2014).

It is noteworthy that all the reported evacuation simulation models assume that all the airline passengers have a very good awareness of aircraft configurations and are able to promptly identify the nearest exit in real emergency situations. In addition, passengers can receive the real-time status of the cabin in evacuation process, including availability of exits, queuing status of exits, and the distance to each exit. Nevertheless, such treatment may not be realistic. As shown in a survey on aircraft exit selection (Togher, Galea, & Lawrence, 2009), 25% (a surprisingly high percentage) of the sampled population have no idea about where exits are located on an aircraft. Moreover, 40% of passengers in the questionnaires believe that all exits on the aircraft are exactly the same in size whereas 23% do not know that exits are different in sizes. Only 23% of the sampled population could correctly locate the position of overwing exits on an aircraft. After being informed of the configuration of an aircraft, 72% of passengers were apt to choose the larger front exit while 25% chose the smaller overwing exits. Yet, this is actually not an optimal exit selection in an emergency evacuation situation. Another investigation conducted by Galea, Finney, Dixon, Siddiqui, and Cooney (2006) based on the 105 survivable crashes with over 2000 survivors reveals that a large number of survival passengers tended to evacuate from the center overwing exits (known as Type-III exit) which are the smallest, and also the least efficient, exits on aircrafts and require a significantly greater amount of time to pass through than the front or rear exits (known as Type-C exit). From the aforementioned reports, it is obvious that a large portion of airline passengers have poor knowledge of aircraft configurations, resulting in a blindness of exit selection in emergency evacuation. They simply move toward the nearest exit without taking account of the flow rate of exits. Insufficient preparation or no instruction in evacuation process would easily cause panic, leading to abnormal evacuation behaviors of passengers, and eventually reduce the emergency evacuation efficiency (Miyoshi et al., 2012). As reported by the NTSB, the injuries in the Asiana Airlines Boeing 777 crash on July 6, 2013 were caused by the inefficient evacuation due to the delayed evacuation instruction from flight crew (US News, 2013). Additionally, exits on an aircraft may not always be available in every survivable crash. As recorded in the AASK V4.0, over 30% of emergency aircraft evacuations have less than 50% of exits available (Galea et al., 2006). If airline passengers cannot promptly locate the available exits in an emergency evacuation, the entire egress time would also be heavily delayed.

To address the aforementioned issues in a real aircraft emergency evacuation, there is an urgent need for developing a guidance system that can guide passengers to evacuate from an aircraft as efficiently as possible via the correct exit selection. Optimized evacuation signs or a guidance system can significantly improve the evacuation efficiency and mitigate severe post-impact fatalities caused by inefficient evacuation. The significance of guidance systems in enhancing evacuation performance has been reported in building evacuation (Luh, Wilkie, Chang, Marsh, & Olderman, 2012; Sagun, Bouchlaghem, & Anumba, 2011; Wang, Luh, Chang, & Marsh, 2009), stadium evacuation (Luh et al., 2012), and disaster evacuation (Kou, Xiong, Fang, Zong, & Chen, 2013; Saadatseresht, Mansourian, & Taleai, 2009), etc. The guidance system in aircraft emergency evacuation, however, has rarely been studied up to date. This paper serves the purpose of proposing an evacuation guidance system to direct passengers located in different positions of a cabin to evacuate from the optimal available exits, so as to improve the evacuation efficiency and correspondingly reduce the entire egress time. Seeking the optimal directions that passengers should choose to evacuate can be essentially viewed as an optimization problem. However, due to the high computational load of the new aircraft evacuation simulation model developed in our earlier work (Liu et al., 2014), which takes account of the variation of egress time resulting from randomness of passengers' physical characteristics, it is computationally unaffordable to enumerate all the possible solutions over the entire feasible domain. The metamodeling technique, the kriging model specifically, is used to alleviate the computational burden by constructing an approximation model for the original evacuation simulation model. By using a sequential sampling strategy, the interpolation uncertainty of the kriging model in the region of interest can be gradually reduced by adaptively adding samples from the evacuation simulation model. To guarantee the globally optimal solution with a high confidence, two decision validation metrics together with a termination criterion are used to validate the final optimal solution. The effectiveness and efficiency of the proposed method are demonstrated in the case studies of Boeing 767-300 and Boeing 747-400.

The main contributions of this work can be summarized as: (1) A direction guidance system is firstly introduced to facilitate aircraft emergency evacuation. As demonstrated in our case studies, the entire egress time can be greatly saved with the assistance of the proposed direction guidance system. (2) A four-stage metamodel-based optimization method which takes account of the metamodeling uncertainty at un-sampled sites is proposed to alleviate the computational load in seeking the optimal evacuation directions. (3) The insights and results delivered in this work would facilitate the aircraft manufacturers' consideration of the direction guidance system in future aircraft design. The rest of this paper is organized as follows: In Section 2, the new aircraft evacuation simulation model proposed in our earlier work is briefly reviewed, and the direction guidance system to be optimized is introduced. The framework of the proposed metamodel-based direction guidance system optimization is first outlined in Section 3, and it is followed by the detailed explanation of the four stages in the proposed method. The case studies of Boeing 767-300 and Boeing 747-400 are elaborated in Section 4 to demonstrate the effectiveness of our proposed method. The conclusion and future works are summarized in Section 5.

2. Aircraft emergency evacuation simulation model

Due to the extremely expensive cost and potential threats of injury to participants, conducting real aircraft evacuation trials are unaffordable, especially for large civil aircrafts. For instance, around 2 million dollars were spent to conduct a single aircraft