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A sequencing model for a team of aircraft landing on the carrier

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ABSTRACT

Safety and efficiency are crucial for landing a team of aircraft in order to improve the combat capability of aircraft carrier. One way to enhance the safety and efficiency level of the landing mission is to optimize the landing sequence. It can shorten the landing time consumption and improve the capacity of deck as well as flight safety. In this paper, a modeling and sequencing approach for landing a team of aircraft is proposed. Firstly, the sequencing problem for landing a team of aircraft (SPLTA) is described by introducing each procedure of the landing mission. The traffic in the terminal area and the strategy for failed-to-land aircraft (FLA) are paid more attention because they are closely related to the SPLTA. Then the state change of a single aircraft in flight and exchanges of aircraft in the terminal area are taken into account. The overall SPLTA is formulated into an optimization problem with a cost function subjected to realistic constraints. To solve the SPLTA, a dynamic sequencing algorithm using ant colony method (DSAAC) is proposed to enable a team of aircraft to land with an optimal sequence. In the experiments, the SPLTA is solved using a "least fuel first service" (LFFS) principle based method, the ant colony optimization algorithm (ACO) based method, the static sequencing algorithm of ant colony (SSAAC) and the DSAAC. It shows that the DSAAC performs better than other three methods in minimizing the cost function and the landing time consumption. Furthermore, DSAAC guarantees a higher level of flight safety and yields an effective response to dynamic circumstance. The DSAAC approach provides an intelligent tool for overall air traffic management on aircraft carrier.

1. Introduction

Having completed the combat mission in the air, a team of aircraft will return to the carrier following the command from the air traffic control center. They reach the appointed airspace and wait for the landing permission [1]. Since there is only one available runway for landing on the deck, aircraft will wait for a long time in the air if they reach the aircraft carrier within a short period [2,3]. As a result, the landing time consumption will increase. Therefore, the capacity of the runway becomes a bottleneck for landing a team of aircraft. The safety and efficiency level are two key factors to evaluate the comprehensive launch and landing ability of a carrier aircraft system [4].

Landing is one of the most dangerous operations on the deck [5]. Aircraft sometimes even need to make another attempt if the previous landing fails. According to the statistics of the U.S. Navy, about only 70% of aircraft can land successfully at the first attempt in the day time, and the succeeding rate is even lower in the night owing to bad visibility [6]. Therefore, optimization of the landing sequence and proposing a reasonable strategy for failed-to-land aircraft (FLA) are significant to enhance the safety and efficiency level during landing a team of aircraft.

Landing a team of aircraft in an optimal sequence can reduce the mission time and improve the deck capacity as well as flight safety. The optimization of landing sequence is a part of air traffic flow management, and the validity of management is the prerequisite of safe and orderly air traffic [7,8]. At present, the management for landing a team of aircraft relies on the judgments of the air traffic controllers (ATC). They make a decision according to information and experiences. It is difficult to provide an optimal solution immediately as the number and types of aircraft increase. Considering the safety of flight and landing, the ATC usually arranges the aircraft with fuel shortage to land with higher priority. This is called "the least fuel first service" (LFFS) principle. The LFFS is a simple approach and can be operated easily in reality. However, it usually lacks consideration of overall efficiency when guiding a landing mission. Considering this shortcoming of LFFS, a large number of researchers have done research in this field to provide optimal solutions for the aircraft sequencing problem (ASP) [9,10].

ASP is a well-known topic in the air traffic management field for civil aviation. Since the ASP problem is classical, most re-

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searchers focus on the algorithm design. For example, their research is aimed at decreasing the computational time, and reducing the response time when taking into account the increasing and relatively large number of flights [11]. The constraints of ASP are comprised of the following: position shift constraints on aircraft [12,13], the minimum space (interval distance) requirement, the constraints on landing time-window and precedence [14]. According to most existing literatures, the cost function for an ASP problem is usually comprised of the total/average airborne delay [15] or takes into account flight economy [16]. Besides, the ASP is an issue which takes into account dynamic changes in environment. The ASP problem can be solved using a receding horizon control approach, where the overall landing sequence is determined based on sequencing results derived for each segment of the queue [17,18].

In the field of traffic management for carrier aircraft, existing literatures mainly focus on path planning and scheduling of post-landing aircraft on the deck [19,20]. Literature about the study of sequencing problem for landing a team of aircraft is limited to Ref. [21] and Ref. [22]. The remaining fuel volume and battle damage of aircraft are considered in the model presented by Ref. [21]. Several sequencing algorithms are presented and compared in Ref. [22], a sliding sequencing window based algorithm is recommended by the author to get the optimal landing sequence.

Similarities exist between the study of ASP with carrier aircraft and the study of ASP with civil aircraft. In both cases, the ASP is transformed into an optimization problem comprised of a cost function and practical constraints. However, for the landing problem of an aircraft carrier the number of aircraft, which are allowed to return at certain time window, is restricted by the deck area, this number is usually much smaller than that of aircraft which are allowed to land on a civil airport at certain time period. In addition, for safety issue consideration, carrier aircraft must satisfy certain conditions before they can get the permission for landing. For example, the aircraft short of fuel must wait for the air refueling tanker before being permitted to land; the aircraft with severe damage has to land on the land base urgently. Besides, there exists high possibility that carrier aircraft fail to land and another landing attempt need to be performed. The chance that carrier aircraft fail to land at the first attempt is much higher than that for civil aircraft.

Except for airborne delay and flight economy, the cost function for an ASP problem should take into account many other factors, e.g., fuel shortage, damage degree of airframe, etc. Existing literatures only considered airborne delay when constructing the cost function [14,18]. Airborne delay is considered in Ref. [15] using a weighted manner, but the physical meaning of the weighting coefficient is not clear enough. Receding horizon control approach is suitable for ASP especially when considering dynamical environment changes. In practice, aircraft may enter or leave the terminal area now and then; this change in the waiting queue has big influence in determining the final optimal landing sequence. However, this influence is ignored by Refs. [17,18]. In addition, in Refs. [17,18] all aircraft are participants of the sequencing procedure all the time, but the terminal area in reality has a limited capacity. This factor is ignored in Refs. [17,18]. It should be mentioned that the state of aircraft, e.g., remaining fuel, is always changing during a flight, therefore, these changes should be considered when constructing the model for solving an ASP problem. These changes are not taken into account by existing literatures [21,22].

This paper establishes a more comprehensive and thus more realistic model for the sequencing problem for landing a team of aircraft (SPLTA). Specifically, the exchange of aircraft in the terminal area is taken into account. The constraints of relative position shift (RPS) between two neighboring sequencing process are also considered. Besides, the strategy for FLA case is proposed and integrated into the sequencing approach to provide a complete solution for the SPLTA.

The main contributions of this study are as follows:

1) The procedures of a landing mission for a team of carrier aircraft are described in detail, and the SPLTA problem is stated with a number of practical issues discussed.
2) A novel modeling method for SPLTA, which considers FLA cases, is proposed. The model considers a variety of factors, for example landing time delay, fuel decrease, the integrity of the airframe, and the pre-attributed task priority of aircraft. The constraints of SPLTA are also included.
3) A solver for SPLTA is developed based on an improved ant colony optimization algorithm (IACO). Two types of experimental simulations are performed to validate the SPLTA model and to demonstrate the efficiency of the IACO based solver. The results show that the proposed modeling method for SPLTA is reasonable and the IACO based solver has better performance, i.e., leading to lower cost function value, than other alternatives in optimizing the landing sequence. It is worthwhile to mention that the proposed modeling method for SPLTA takes into account FLA cases.

The outline of this paper is as follows. In section 2, problem statement for the SPLTA is given. A mathematical model reflecting dynamic circumstance changes is formulated for the SPLTA in section 3. Sequencing rules and optimization algorithms are developed by section 4. In section 5, validation results and the analysis is given. This paper is concluded by section 6.

2. Background of the SPLTA

The landing of aircraft is a multi-step mission, and each procedure is directed by different staffs and equipment. Firstly, each procedure of the landing mission is described. Then the traffic in the terminal area associated with the SPLTA is highlighted. Thirdly, the strategy for FLA is proposed to ensure an effective response to an FLA case. The conceptual model of SPLTA is presented at the end of this section.

2.1. Description of the landing mission

The aircraft is instructed by the airborne early warning (AEW) when it completes the combat mission and returns to the aircraft carrier. The AEW guides the aircraft to make the return route correct. About 200 nautical miles away from the aircraft carrier, the aircraft follows the command of ATC from the air traffic control center [23]. It is an important procedure in landing mission that decides whether the aircraft is permitted to land under the current state. If the landing is permitted, the aircraft flies towards the terminal area, joins to the landing sequence and adjusts its position in the landing sequence according to the results of executing the sequencing algorithm. The aircraft refused to land will follow the command of the air traffic control center.

About 50 nautical miles away from the aircraft carrier, the landing mission comes into a procedure called approach control [23]. The aircraft informs the carrier of the flight state continuously and receives the information on position and sail of the carrier. The route is corrected constantly under the command of the airborne control center. When the aircraft is 20 nautical miles away from the aircraft carrier, the landing console operator (LCO) sends the aircraft the landing mode, the arresting mode and the start position of landing [24]. Before receiving the command of landing, the aircraft still circles in the predetermined holding pattern.

Once having received the command of landing, the aircraft approaches to the aircraft carrier and lands on the runway deck