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Distributed free-flow-traffic management system based on Nash equilibrium concept

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국문 요약

여객수요증가와 보다 다양한 저수요 목적지를 포괄하는 소형 항공사 시장의 성장으로 인해 향후 항공교통체증이 크게 증가할 것으로 예상된다. 자율비행택시, 차량 등 새로운 미래 모빌리티(항공, 지상, 해상)가 등장하면서 가까운 미래에 상용화를 준비하는 것 역시 새로운 항공교통량 증가를 유발하는 요인으로 운송관리 능력에 의문이 제기되고 있다. 그러나 현재 활용되고 있는 중앙집중형(centralized) ATM 시스템은 속도 측면이나 불확실성에 대한 대응 측면에서 미래 항공여행의 특성에 효과적으로 대처할 수 없는 것이 현실이다. 이 연구는 최소한의 통신으로 미래 모빌리티의 복잡한 특성을 고려하여 자유흐름(Free-Flow)을 관리하기 위한 분산형 교통관제시스템(Traffic Management System)을 제안한다. 최소한의 의사소통으로 분산형 교통 관리가 이뤄지는 상황을 비협조적 게임 (Uncooperative Game) 상황으로 인식하고, 이를 해결하기 위한 내쉬 균형 (Nash Equilibrium) 개념을 도입하였다. 이러한 방법을 이용하여 전체 시스템에 걸쳐 계산 부담과 위험이 분산되게 되어 기존의 중앙집중형 알고리즘의 문제점을 해결할 수 있게 된다. 내쉬 균형 개념에 기반하여 각 에이전트가 취해야 하는 속도 변화량과 방향 변화량을 계산하여 충돌 방지를 수행할 수 있게 된다. 기존 기법(Myopic Algorithm)과의 비교를 통하여 제안된 기법의 성능을 보였다.

Introduction

Future air traffic congestion is expected to rise significantly owing to an increasing number of passengers and the growth of small-sized airline markets. However, the current centralized ATM system cannot handle the characteristics of future air travel effectively because of its slow data process, vulnerability to uncertainty, and centralized risk. In this research, a distributed traffic management system (TMS) to deal with the complex nature of future mobility with minimal communication demand is introduced. The TMS is also required to control multiple free-flowing agents under complex situations effectively and robustly (See Fig. 1).

Fig. 1: Decentralized free-flows found in daily surroundings

The system introduced in this research allows each agent to decide which action should be taken with low-level information exchange among agents. The concept of Nash equilibrium is introduced to realize the distributed free-flow TMS; Since the situation of traffic management with minimal communication is one type of uncooperative gaming situation.

Nash Equilibrium Concept for Traffic Management System

The conflict is a situation where the projected distance between two agents is closer than the threshold distance. To resolve conflict, both agents should maneuver to increase their projected distance by changing the direction or velocity. Allocating the deviations responsible for different agents is the decision that the system has to make. We introduce the fairness and safety concepts to determine the deviation of each agent. For the amount of deviation that two agents i and j (D_{ij}), the fairness utility function (= $(k_i x_i - k_j x_j)^2$) represents the reflection of the urgency to the deviation, and the safety utility function (= $(x_i + x_j - D_{ij})^2$) represents the level of excessive deviation compared to the required value (k_i: urgency level of an agent). The Nash equilibrium for the deviation between the two agents (x_{ij}^{NE}) can be obtained based on the two utility functions. We determine the Nash equilibrium points for more than two agents by minimizing the non-compliance function ($J_i(x_i) = \sum_j k_j (x_i - x_{ij}^{NE})^2$). Fig. 2 shows the Nash equilibrium points for four agents subject to a simultaneous conflict, which are the best responses (BR).

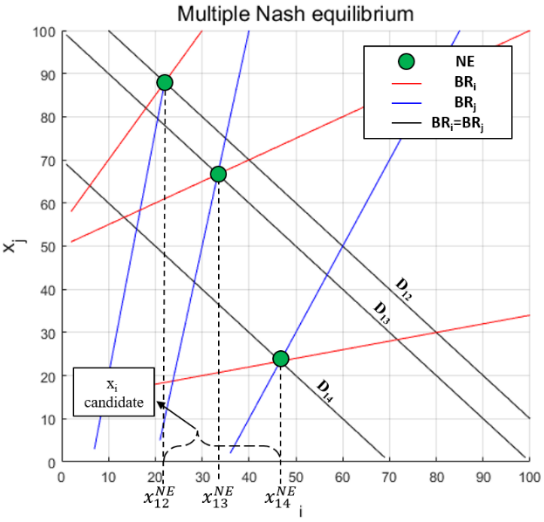


Fig. 2: The best response (BR) plot for simultaneous conflict situation with four agents

After the Nash equilibria are determined, we can compute the allocated deviations ($d\theta_{aloc} = \frac{1}{ETA\ v} \frac{\sum k_j x_{ij}^{NE}}{\sum k_j}$: allocated direction deviation, $dv_{aloc} = \frac{1}{cos\theta} \frac{\sum k_j x_{ij}^{NE}}{\sum k_j}$: allocated speed deviation) using the equilibria (ETA: time to the closest point).

Numerical Simulation

The objective of the simulation is to demonstrate the performance of the proposed Nash equilibrium algorithm compared to the myopic algorithm. The simulation uses three algorithms: the naïve Nash, the urgency-considered Nash, and the Myopic. We introduce performance metrics: the domino effect parameter (DEP), the total deviation effort (TDE), the TDE ratio, the traffic density, and the minimum distance observed (MDO). Multiple agent types representing various vehicles are considered. Fig. 3 shows the simulation results representing the center conflicts. Fig. 4 compares the performance of different algorithms based on the minimum distance observed (MDO) metric. The Naïve Nash shows the best distancing capability. The urgency-considered Nash algorithm performs significantly better than the Myopic algorithm, demonstrating its potential to be used for the TMS of future mobility.

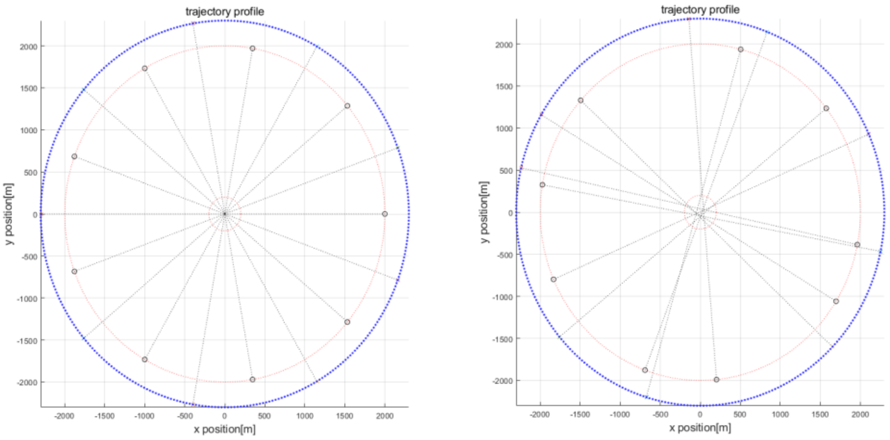
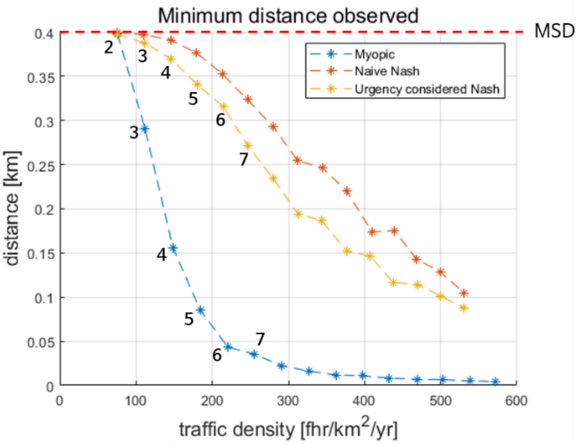


Fig. 3: Two types of center conflicts; Choke (left) and Randomly converging (right)



* Bold number shows number of agents

Fig. 4: Comparison of minimum distance metric for different traffic management algorithms

Conclusion

The proposed algorithm demonstrated the potential of a distributed free-flow-traffic management system in various traffic situations. The algorithm can effectively keep a safe distance among agents under highly complex situations while performing priority management – without complex communication and computation. It showed the applicability for various traffic types, demonstrated by the numerical simulation, and can be used as a universal framework to solve complex traffic management of future mobility.

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