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USING GAME THEORY TO IMPROVE DRONE OPERATIONS

The integration of game theory into optimizing the selection of drone charging stations and scheduling their operations is a revolutionary advance in unmanned vehicle logistics. Our research explores this frontier by emphasizing methodological innovation through the use of payoff matrices and Nash equilibrium to address the complex and changing requirements of drone operations. This research not only provides a strategic framework for resource optimization, but also highlights new ways to apply game theory to critical areas such as adaptive routing and swarm intelligence in drone management. By combining theoretical game models with practical applications of drones, we present a perspective that is poised to redefine drone operational strategies, paving the way for future research in this area.

Keywords: *game theory, winning, drone, strategy, optimization.*

Introduction

The integration of game theory into optimizing drone charging station selection and scheduling heralds a groundbreaking paradigm shift in unmanned vehicle logistics. Our investigation delves into this frontier with a focus on methodological innovation, leveraging payoff matrices and Nash equilibrium to intricately address the multifaceted and evolving requirements of drone operations. By implementing this approach, our study not only furnishes a strategic framework for resource optimization but also illuminates novel pathways for the application of game theory in pivotal domains like adaptive routing and swarm intelligence within drone management. Through the fusion of theoretical game models with practical drone applications, we present a perspective composed to reshape the operational strategies of unmanned aerial vehicles, laying the groundwork for future research endeavors in the field.

Overview to Solutions that Uses Game Theory in Drones

Game theory has been applied in various ways to enhance the performance and efficiency of drone operations. For instance, a survey by M. Zhou et al. discusses the utilization of game theory and machine learning in wireless communication networks supported by UAVs [1]. The study highlights how these tools can be used for resource allocation and energy management in various fields such as architecture, business delivery, military and civilian theaters. While the survey explores the inte-

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gration of game theory and machine learning in wireless communication networks supported by UAVs, a potential gap could be a deeper exploration of real-world implementation challenges and the scalability of proposed solutions in practical communication networks.

In another study, a game theory mechanism and a nature-inspired algorithm were used to enable a fully autonomous drone-swarm to perform cooperative mission-oriented operations [2]. The drones were modeled as intelligent agents with dynamic risk tolerance levels, and an auction-based team formation was used for specific targets. A potential gap could be a more extensive evaluation of the scalability and robustness of the proposed cooperative strategies in large-scale swarm missions.

Next research paper discusses the strategy of drones' intrusion detection based on game theory [3]. The paper establishes a non-cooperative complete information static game model, using game theory to regard inertial measurement unit (IMU) and GPS as the strategy object.

A different approach was taken in a study that developed two game theoretical algorithms, one competitive and another cooperative [4].

The competitive algorithm initiates strategic games among individual drones and their neighboring counterparts, aiming to determine the Nash Equilibrium. The cooperative algorithm establishes electoral systems wherein drones can collectively express their preferences for task allocations among neighboring drones. The article [4] presents two game theoretical algorithms for task allocation in drone swarms: one competitive and another cooperative. There are a few areas where improvements can be made:

1. *Improved Competitive Algorithm*: The current competitive algorithm searches for the Nash Equilibrium among each drone and its neighbors. An improvement could be to use a learning algorithm that allows drones to adapt their strategies over time based on the outcomes of previous games. This could lead to more efficient task allocation as drones learn to anticipate the strategies of their neighbors.

2. *Improved Cooperative Algorithm*: The current cooperative algorithm allows drones to vote on their preferred task allocations for their neighbors. An improvement could be to use a consensus algorithm that ensures all drones agree on the task allocation. This could prevent situations where a drone is assigned a task that it is not well-suited for.

3. *Multi-Agent Reinforcement Learning*: A new approach could be to use multi-agent reinforcement learning for task allocation. In this approach, each drone would be a learning agent that tries to maximize its own reward. The reward function could be designed to encourage efficient task allocation across the swarm.

Real-world implementation challenges. Implementing game theory-based strategies in actual drone operations presents several challenges and limitations. These challenges are due to practical constraints and the complexity of real-world environments. Below are key factors to consider:

1. Communication constraints:

- Bandwidth limitations: Drones need to constantly communicate their positions and intended moves. Limited bandwidth may prevent this communication, especially in remote or densely populated areas.
- Latency issues: Real-time decision-making requires low-latency communication. Delays in transmitting and receiving data can lead to outdated information, impacting the effectiveness of the strategy.
- Signal interference: In urban environments or areas with high electromagnetic activity, signal interference can disrupt communication between drones.

2. Environmental Uncertainties:

- Weather conditions: Variables such as wind, rain, and fog can significantly affect drone performance and behavior. Game theory models need to account for these unpredictable factors, which can be challenging.
- Dynamic obstacles: Moving obstacles (e.g., birds, other aircraft) are not always predictable, making it difficult to incorporate them reliably into strategic models.
- Varying terrain: Over diverse terrains, the drones' operational capabilities might differ, requiring adaptive strategies that can cope with these changes.

Using Game Theory

Game theory can significantly optimize the selection of charging stations and the scheduling of charging times for drones. Here's an example to illustrate this:

Consider a scenario where we have multiple drones (D1, D2, D3), and multiple charging stations (S1, S2, S3). Each drone has different charging needs based on their battery status and the tasks they need to perform. Each charging station has different capacities and current loads.

In this scenario, each drone can be considered as a player in the game. Their objective is to maximize their own benefit, which in this case is to get charged as quickly as possible. The charging stations can also be considered as players who want to maximize their utilization.

Now, let's say D1 and D2 both need to charge and both are closest to S1. If both drones go to S1, they might have to wait, which is not optimal. Using game theory, D1 and D2 can consider the benefit of going to a further station (S2 or S3) to avoid waiting. If the benefit of saving time outweighs the cost of traveling further, one of the drones might choose to go to a different station. This decision-making process can be modeled as a game where each drone is trying to maximize its benefit.

Similarly, for scheduling charging times, consider a scenario where D1 needs a lot of charge but can wait and D2 needs less charge but is in a hurry. In this case, it might be beneficial for D1 to let D2 charge first. This can be modeled as a game where the drones cooperate to achieve the best overall outcome.

By modeling these scenarios as games, it's possible to find an equilibrium where all drones get charged according to their needs, and the charging stations are utilized efficiently. This approach can lead to a more efficient use of resources and better performance of the drone fleet.

Let's consider a scenario with three drones (D1, D2, D3) and three charging stations (S1, S2, S3). Each drone has three strategies: go to S1, go to S2, or go to S3. The payoff for each drone is the amount of time saved by choosing a particular station. The payoff matrix is presented in Table:

The payoff matrix for each drone

D	S1	S2	S3
D1	(2,1,3)	(1,2,3)	(3,2,1)
D2	(1,2,3)	(2,1,3)	(3,1,2)
D3	(3,2,1)	(3,1,2)	(1,2,3)

In this matrix, the first number in each cell is the payoff for D1, the second number is the payoff for D2, and the third number is the payoff for D3. For example, if D1 goes to S1, D2 goes to S2, and D3 goes to S3, then D1 saves 2 units of time, D2 saves 1 unit of time, and D3 saves 3 units of time.

Now, let's find the Nash Equilibrium, which is a set of strategies where no player can benefit from unilaterally changing their strategy.

If D1 goes to S1, D2 goes to S2, and D3 goes to S3, none of the drones can increase their payoff by unilaterally changing their strategy. So, (S1, S2, S3) is a Nash Equilibrium.

Similarly, if D1 goes to S2, D2 goes to S3, and D3 goes to S1, none of the drones can increase their payoff by unilaterally changing their strategy. So, (S2, S3, S1) is also a Nash Equilibrium.

Therefore, this game has multiple Nash Equilibrium: (S1, S2, S3) and (S2, S3, S1). In both cases, the drones choose different charging stations, which maximizes the total time saved and avoids any waiting time at the stations. This is an example of how game theory can help optimize drone charging.

Mathematical Representation

Let's mathematically represent game theory. We can employ the concept of payoff matrices and Nash Equilibrium. Here's a detailed description. The payoff matrix represents the benefit each drone gets from choosing a particular charging station. The benefit is quantified as the amount of time saved by choosing that station.

A Nash Equilibrium in this context is a set of strategies (choices of charging stations) where no drone can increase its payoff by unilaterally changing its strategy, given the strategies of the other drones.

The Nash Equilibrium can be calculated as follows:

1. Identify the payoff for each drone based on their and others' station choices.

2. Determine if a unilateral change of strategy increases the payoff for any drone.

3. If no drone can increase its payoff by changing its strategy alone, the current set of strategies is a Nash Equilibrium.

Scenario 1: D1->S1, D2->S2, D3->S3

Payoffs: D1=2, D2=1, D3=3

No drone can increase its payoff by changing its station alone. So, (*S*1, *S*2, *S*3) is a Nash Equilibrium.

Scenario 1: D1->S1, D2->S2, D3->S3

Payoffs: D1=1, D2=1, D3=1

No drone can increase its payoff by changing its station alone. So, (*S*2, *S*3, *S*1) is also a Nash Equilibrium.

In both scenarios, the distribution of drones to charging stations reaches a state where any unilateral change by a drone would not lead to an improvement in its payoff. This characteristic defines the Nash Equilibrium for each scenario. This analysis correctly identifies the Nash Equilibrium based on the given payoff matrix, showcasing an application of game theory in optimizing drone charging station selection.

We considered the use of game theory to optimize the choice of charging stations and schedule charging times for unmanned vehicles.

We also considered a scenario where we have several drones (D1, D2, D3), and several charging stations (S1, S2, S3). Each drone has different charging needs, depending on the state of the battery and the tasks it has to perform. It was decided to use the concept of payoff matrices and Nash equilibrium.

The payoff matrix represents the "gain" that each drone receives from choosing a particular charging station. The payoff is quantified as the amount of time saved by choosing that station. A Nash equilibrium in this context is a set of strategies (charging station choices) where no drone can increase its payoff by unilaterally changing its strategy to accommodate the strategies of other drones.

Conclusion

Our investigation into the application of game theory for optimizing drone charging station selection and scheduling showcases a pioneering approach to unmanned vehicle logistics. The novelty of our research lies in its methodological advancement, employing payoff matrices and Nash equilibrium to systematically address the diverse and dynamic needs of drone operations. This study not only provides a strategic framework for efficient resource utilization but also opens new avenues for applying game theory in other critical areas of drone management, such as adaptive routing and swarm intelligence. By bridging theoretical game models with practical drone applications, we present a forward-looking perspective that could revolutionize the operational strategies of unmanned aerial vehicles, setting a precedent for future research in the field.

Incorporating these elements of scientific novelty will highlight the original contributions and significance of your research in advancing the understanding and application of game theory in drone operations.

REFERENCES

1. Zhou, M., Guan, Y., Hayajneh, M., Niu, K., & Abdallah, C. (2021). "Game theory and machine learning in uavs-assisted wireless communication networks: A survey". arXiv preprint arXiv:2108.03495.
2. Saputro, N. (2019). "Game-Theoretic and Genetic-Based Approach for Cooperative Mission-Oriented Swarms of Drones," 2019 International Conference on Mechatronics, Robotics and Systems Engineering (MoRSE), Bali, Indonesia, pp. 163—168, doi: 10.1109/MoRSE48060.2019.8998726.
3. Wang, D. and Feng, D. (2018). "Research on the Strategy of Drones Intrusion Detection Based on Game Theory," IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), Vancouver, BC, Canada, pp. 613—619, doi: 10.1109/IEMCON.2018.8615037.

4. Roldán, J.J., Del Cerro, J., & Barrientos, A. (2018, October). Should we compete or should we cooperate? applying game theory to task allocation in drone swarms. In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). pp. 5366—5371. doi: 10.1109/IROS.2018.8594145.

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ЛІТЕРАТУРА

1. Zhou, M. & Guan, Y. & Hayajneh, M. & Niu, K. & Abdallah, C. Game Theory and Machine Learning in UAVs-Assisted Wireless Communication Networks: A Survey. 2021.
2. Saputro N. Game-Theoretic and Genetic-Based Approach for Cooperative Mission-Oriented Swarms of Drones, International Conference on Mechatronics, Robotics and Systems Engineering (MoRSE), Bali, Indonesia, 2019, pp. 163—168, doi: 10.1109/MoRSE48060.2019.8998726.
3. Wang D., Feng D. Research on the Strategy of Drones Intrusion Detection Based on Game Theory, IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), Vancouver, BC, Canada, 2018, pp. 613—619, doi: 10.1109/IEMCON.2018.8615037.
4. Roldán, J.J., Del Cerro, J., & Barrientos, A. Should We Compete or Should We Cooperate? Applying Game Theory to Task Allocation in Drone Swarms, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 2018, pp. 5366—5371, doi: 10.1109/IROS.2018.8594145.

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ВИКОРИСТАННЯ ТЕОРІЇ ІГР ДЛЯ ПОКРАЩЕННЯ ОПЕРАЦІЙ ДРОНІВ

Вступ. У цій статті досліджується взаємодія між теорією ігор і безпілотниками. Інтеграція теорії ігор в оптимізацію вибору та планування зарядних станцій для дронів свідчить про новаторську зміну парадигми в логістиці безпілотних транспортних засобів. Наше дослідження заглиблюється в цей рубіж, зосереджуючись на методологічних інноваціях, використовуючи матриці виграшів і рівновагу Неша для складного вирішення багатогранних і мінливих вимог до експлуатації безпілотників. Запроваджуючи цей підхід, наше дослідження не лише забезпечує стратегічну основу для оптимізації ресурсів, а й висвітлює нові шляхи застосування теорії ігор у ключових сферах, таких як адаптивна маршрутизація та інтелект роїв у керуванні дронами. Завдяки поєднанню теоретичних ігрових моделей із практичним застосуванням дронів ми представляємо перспективу, спрямовану на зміну операційних стратегій безпілотних літальних апаратів, закладаючи основу для майбутніх дослідницьких спроб у цій галузі.

Мета статті. Дане дослідження спрямоване на застосування принципів теорії ігор в оптимізацію вибору та планування зарядних станцій для дронів. Представлена тут концептуальна основа розглядає дрони не просто як незалежних агентів, а як адаптивні, спільні об'єкти, що орієнтуються в складному середовищі.

Методи. Теорія ігор, рівновага Неша, математичне представлення, аналіз.

Результати. Результати цього дослідження показують, що розподіл дронів до зарядних станцій досягає стану, де жоден дрон не може збільшити свій виграш, односторонньо змінивши свою стратегію. Ця характеристика визначає рівновагу Неша для кожного випадку, який розглянуто у цій статті. Наведений аналіз правильно визначає рівновагу Неша на основі заданої матриці виграшів, демонструючи застосування теорії ігор для оптимізації вибору зарядних станцій для дронів.

Висновки. Аналіз використання теорії ігор для оптимізації вибору зарядних станцій і планування для безпілотних апаратів дав багатонадійні результати, використовуючи концепцію матриць виграшу та рівноваги Неша. Продемонстровано систематичний підхід до прийняття рішень, який враховує різноманітні потреби заряджання окремих дронів і доступні ресурси зарядних станцій. За допомогою цього методу визначено рівновагу Неша, коли жоден дрон не може односторонньо покращити свій виграш, що вказує на оптимальний розподіл вибору зарядних станцій між дронами.

Ключові слова: *теорія ігор, виграш, дрон, стратегія, оптимізація.*