Flight Patterns for Swarms of Drones

Shuqin Zhu, Shahram Ghandeharizadeh
Computer Science Department, University of Southern California
Los Angeles, California, USA
{shuqinzh,shahram}@usc.edu

ABSTRACT

We present flight patterns for a collision-free passage of swarms of drones through one or more openings. The narrow openings provide drones with access to an infrastructure component such as charging stations to charge their depleted batteries and hangars for storage. The flight patterns are a staging area (queues) that match the rate at which an infrastructure component and its openings process drones. They prevent collisions and may implement different policies that control the order in which drones pass through an opening. We illustrate the flight patterns with a 3D display that uses drones configured with light sources to illuminate shapes.

Holodecks Reference Format:
Shuqin Zhu, Shahram Ghandeharizadeh. Flight Patterns for Swarms of Drones. Holodecks, 1(1): 29-33, 2023.
doi:10.61981/ZFSH2303

Holodecks Artifact Availability:
A circular flight pattern in a horizontal, vertical, and diagonal alignments are shown at https://youtu.be/oT5RR8RPl0I, https://youtu.be/TQM4hMBwLHM, and https://youtu.be/NNlWn9VW894, respectively. The speed of the drones is 1 meter/second.

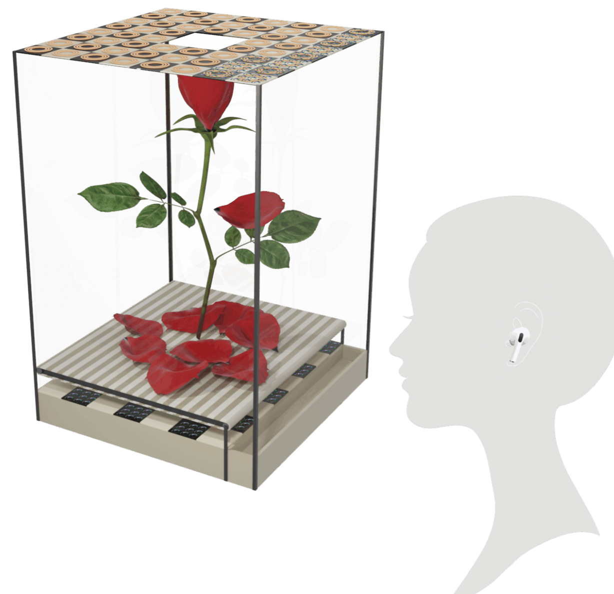


Figure 1: A Dronevision (DV) with charging stations at the top of the display. FLSs with depleted batteries fly through the narrow horizontal opening at the top to land on a charging station and charge their batteries.

1 INTRODUCTION

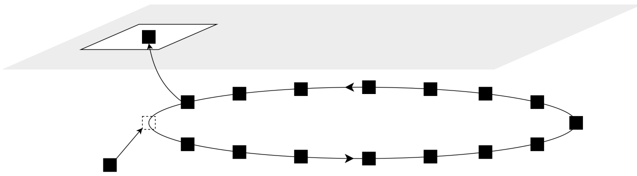
Unmanned Aerial Vehicles (UAVs), drones, are used in diverse applications such as holodecks [11, 12], haptic interactions [1, 3, 6], package delivery [5, 15, 23], information gathering [9], search for and track targets [25], and disaster relief and rescue [22, 27]. The architecture of a system may require a swarm of drones to pass through one or more openings to access an infrastructure component such as charging (refueling) stations, hangars for permanent storage of drones among others. This paper presents flight patterns for collision-free passage of drones through an opening. A flight pattern is a temporary staging area for the drones before they pass through an opening. It may organize drones in a queue, allowing one drone to arrive at the opening at a time and gain entry to the infrastructure.

To simplify discussion and without loss of generality, we focus on a 3D display using the Flying Light Specks, FLSs [11]. An FLS is a miniature sized drone configured with light sources. It has its own processor, storage, and networking card. A swarm of FLSs cooperate to illuminate complex 2D and 3D shapes and animated sequences [11, 12]. An illumination may require a large swarm consisting of millions and billions of FLSs [11]. Once the display of an illumination ends, FLSs must fly back to their hangars for storage. Similarly, our current FLSs are battery powered with a fixed flight time on a fully charged battery. They must fly to a charging station to charge their battery.

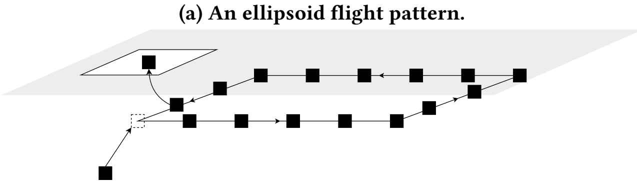
Today's display architectures [2, 12] provide narrow openings for FLSs to access the hangers, charging stations, or both. A challenge is how to provide FLSs with a collision free passage through these opening. To illustrate, Figure 1 shows the architecture of the Dronevision (DV) with glass panes on its side to protect a user from rogue FLSs [2]. The top panel has an opening on the side that enables FLSs to fly through to access the charging stations. The rods on the side are silos that enable the FLSs to be deposited to the hangars at the base of the display. An advantage of this architecture is that it minimizes the likelihood of failed FLSs from falling on and damaging those FLSs in transit to charge their batteries.

A narrow opening raises the following challenge: How to provide collision-free passage to a large number of FLSs trying to fly through one or more of these openings at the same time? “Large" because hundreds of FLSs may want to charge their battery at the same time, see discussion of STAG [12] in Section 3. Similarly, when a

Proceedings of the Holodecks Foundation, Vol. 1, No. 1.
doi:10.61981/ZFSH2303



(a) An ellipsoid flight pattern.



(b) A rectangular flight pattern.

Figure 2: Geometric shaped flight patterns.

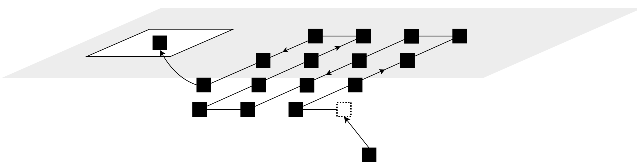


Figure 3: The Zig-Zag line flight pattern.

display is shut-down, a large number of FLSs will fly back to be stored in a hanager at the same time.

A key requirement is for an FLS to arrive at its destination as fast as possible, minimizing its transit time. This enables an FLS to arrive at a charging station with the most flight time remaining, reducing the time the FLS spends charging its battery[1]. In addition, we want to give a higher priority to those FLSs with a lower flight time. This prevents FLSs from failing by exhausting their battery life time prior to arriving at a charging station in a timely manner.

One approach to satisfy these requirements is to introduce flight patterns. A flight pattern organizes FLSs in queues to fly through an openings one at a time. This approach has several advantages. First, the likelihood of one or more FLSs colliding is reduced. Second, once admitted in a queue, FLSs may cooperate and re-order themselves to implement different policies. An example policy may be to minimize the number of FLSs that fail due to exhausting their battery's remaining flight time. A mechanism to implement this policy may be to allow the FLS with the least remaining flight time to move to the head of the queue.

The **contributions** of this paper is the concept of flight patterns for a swarm of drones with a focus on FLSs, see Section 2. We describe the related work in Section 3. Brief future work is detailed in Section 4.

2 FLIGHT PATTERNS

We assume an infrastructure such as a hangar or a charging station has an admission rate of λ FLSs per unit of time. An opening is a component of the infrastructure. We assume the infrastructure

[1]In turn, this frees the charging station for use by other FLSs, reducing the total number of charging stations.

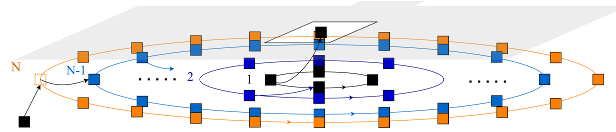
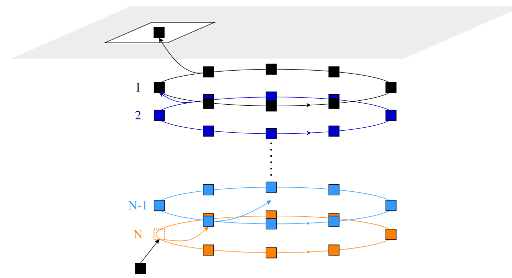
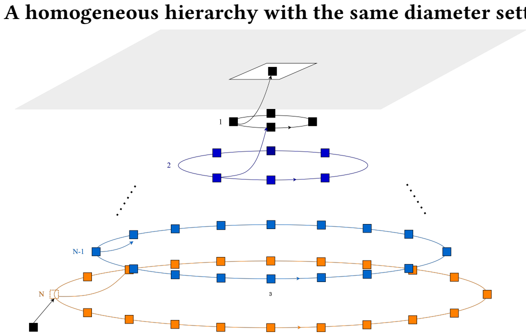


Figure 4: The 2D hierarchical pattern using ellipsoids.



(a) A homogeneous hierarchy with the same diameter setting.



(b) A homogeneous hierarchy with different diameter settings.

Figure 5: A homogeneous hierarchical pattern using circles.

is accessible by one opening. Extensions to multiple opening are described in Section 2.1. With this assumption, the opening may admit one FLS every $\frac{1}{\lambda}$ time units. To illustrate, with λ=10 FLSs per second, the opening allows one FLS to pass through every 100 milliseconds.

A flight pattern consists of a fixed number of slots M, one per FLS. The pattern terminates at the opening for an infrastructure component, e.g., a charging station or a hanger. The slots are interleaved $\frac{1}{\lambda}$ time units apart. This in combination with the distance between two slots of the pattern dictate the speed of each FLS.

Flight patterns may either be geometric or non-geometric. A geometric pattern may be a circle, an ellipsoid, a rectangle, etc., see Figure 2. See https://youtu.be/oT5RR8RPl0I for a circular flight pattern in a horizontal alignment. A non-geometric pattern may be a zig-zag line such as those found in a busy airport or a popular theme park, see Figure 3.

A pattern may be organized in a 2D or a 3D hierarchy. A 2D hierarchy consists of N patterns, say an ellipsoid, with pattern i containing pattern $i-1$. Figure 4 shows a horizontal pattern. Other alignments are possible as discussed in Section 4.

A 3D hierarchy stacks the N patterns atop of one another. The participating patterns may be either homogeneous or heterogeneous. A homogeneous hierarchy consists of the same pattern with

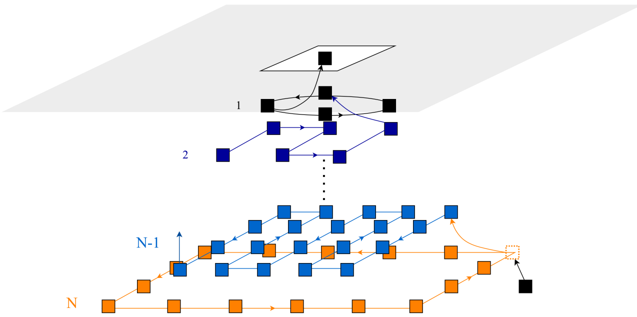


Figure 6: A 3D heterogeneous hierarchy using different patterns.

either identical or different settings. For example, circles with either the same or different diameters, see Figure 5. A heterogeneous hierarchy consists of different patterns. Figure 6 shows an example consisting of ellipsoid, rectangle, and zig-zag lines.

A centralized Orchestrator [12] may manage the slots of a flight pattern. An FLS that wants to enter an opening contacts the Orchestrator and the Orchestrator assigns the last available slot to the FLS. The coordinates of this slot depends on the number of queued FLSs. If there are no queued FLSs then its coordinates are the opening. Otherwise, it is the coordinates of the next empty slot in a queue. Figures 2-6 show the worst case scenario where M-1 slots of a pattern are occupied by an FLS. FLSs in a queue may communicate and switch positions to implement a policy, e.g., move the FLS with the least amount of remaining flight time to the head of the queue.

2.1 Multiple Openings

With multiple openings, the relationship between an opening and the infrastructure may either be exclusive, shared, or hybrid. With exclusive, the infrastructure is partitioned across the Θ openings, each with its own admission rate, $\{\lambda_1, \lambda_2, ..., \lambda_\Theta\}$. A challenge is how to distribute the FLSs across the partitioned infrastructure instances and their openings.

Shared allows an opening to provide access to the infrastructure in its entirety. We assume the total consumption rate of the openings equals λ, $\sum_{i=1}^{\Theta} \lambda_i = \lambda$. A challenge is how to distribute the FLSs across the Θ openings. When every opening has a queue of FLSs, a simple technique may assign an FLS to the opening with the shortest queue while considering factors such as distance, the remaining battery flight time of the FLS, and the consumption rate of an opening λ_i.

With hybrid, the infrastructure is partitioned such that one or more partitions may have multiple openings while others have one opening. It must address the challenges faced by both exclusive and shared for the different openings.

3 RELATED WORK

To the best of our knowledge, the concept of collision-free flight patterns for swarms of drones is novel and not described elsewhere. The concept does exist in aviation with air-planes following a pattern dictated by a control tower to land at busy airports [4]. The control tower is equivalent to a centralized Orchestrator that assigns slots to drones to provide a collision-free landing.

There is a signficant body of work on scheduling drones for communication by extending the radio range of devices, delivery of packages in an order that maximizing profits, among others. See [24] for a survey of these studies. A study may use optimization techniques to schedule the way-points visited by a drone. None present flight patterns for a swarm of drones. Some of the scheduling techniques motivate the flight patterns of this study. For example, STAG [12] is a scheduling technique that staggers the remaining flight time of FLSs to prevent all FLSs from exhausting their flight time at the same time. It switches the place of a fully charged FLS with one that has almost depleted its battery every S interval of time. This staggering interval is dictated by the time for an FLS with an almost depleted battery to arrive at a charging station.

With a large number of FLSs, STAG constructs h flocks, resulting in h FLSs in transit from an illumination to a charging station every S interval of time. In [12], we analyze an illuminated rose consisting of 65K FLSs. Each FLS has a 5 minute flight time on a fully charged battery and requires 10 minutes to charge its depleted battery fully. The rose requires h=218 FLSs in transit with a staggering interval of 1.36 seconds. This is a large number of FLSs traveling to a charging station. No collision-free technique is presented in [12], motivating the flight patters presented in this paper.

A large number of studies present techniques to either avoid [20, 26, 30] or detect and prevent [8, 10, 21, 31, 33] collisions. These studies may use optimization techniques [13, 19, 32], search and planning techniques [17, 28, 29], reinforcement learning [7, 14, 18], and nature inspired techniques [16, 34]. While they do not present flight patterns, one or more of these techniques may be used to control how drones fly to gain access to their assigned slot in a pattern. Similarly, they can be used to control how two or more FLSs may switch positions in a queue.

4 CONCLUSIONS AND FUTURE RESEARCH

Flight patterns provide a collision free passage through one or more opening for swarms of drones. These openings may provide access to a charging station or a hangar for storage of the drones. The flight patterns are queues that require drones to travel at a certain speed that matches the consumption rate of the infrastructure corresponding to the opening, e.g., hangar, charging station, etc. These patterns were presented in a horizontal setting for a narrow opening at the top of a display. However, they may be formed in any alignment. For example, a vertical formation may be appropriate for the Dronevision of Figure 7. The concept of flight patterns raises many interesting research topics. We present a few in the rest of this section.

Drones may be assigned to the slots using either a centralized or a decentralized algorithm. With both, drones should be able to communicate to implement gossip based protocols. A drone in a queue may communicate with the drones in its radio range, e.g., those drones behind, ahead, above, and below it. A message may contain its neighbor's metadata, e.g., remaining flight time. This information enables two or more drones to implement different policies for managing their ordering in the queue. Details of how

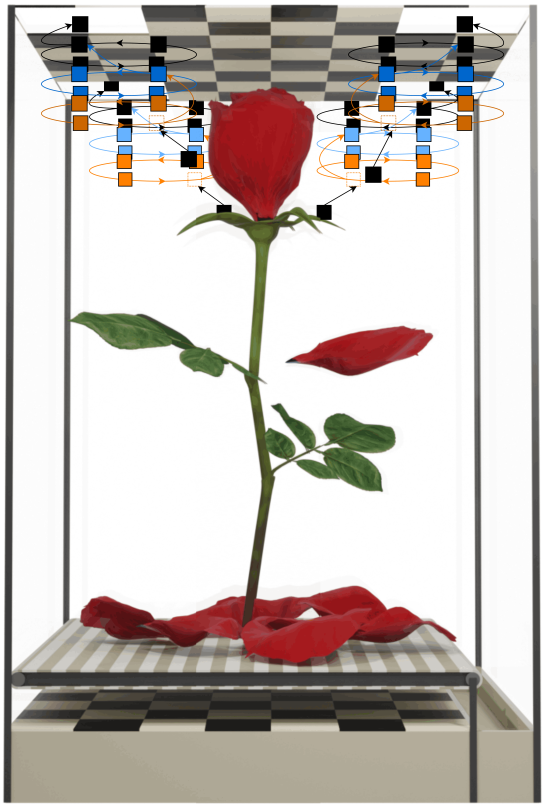


Figure 8: Charged FLSs join the bottom of the rose illumination. They move up in an orderly manner. Those with almost depleted batteries at the top of the illumination. These FLSs are scheduled in flight patterns for one of the four openings that provide them with access to the charging coils.

Figure 7: A Dronevision (DV) with charging stations behind a wall at the back of the display. FLSs with depleted batteries fly through the narrow vertical opening to land on a charging station and charge their batteries.

drones change position in a collision free manner are also a future research direction.

It is important to gain insight into the alternative flight patterns and their tradeoffs. This is a multi-faceted topic. It includes the characteristics and limitations of drones as a dimension. For example, a limitation of FLSs is that they fail [11]. There are different forms of failures including those that cause the FLS to stop flying all together, dropping to the floor of the display. It is important to understand which flight patterns are more tolerant of FLS failures. In specific, the failure of an FLS and how it may fall on the FLSs below it is an open research topic.

With FLSs, a flight pattern may synergize with an illumination. For example, in Figure 8, FLSs with fully charged batteries may join the bottom of an illumination. They move up to the top of the display based on a regular schedule. Their battery is almost depleted once they arrive at the very top, causing them to join a flight pattern at one of the entries to access a charging station. A key question is what happens to the FLSs illuminating the falling petal. A possible answer is to have a subset of the FLSs move up the illumination more rapidly to illuminate the falling petal. An investigation of this question and the overall approach is a future research direction.

ACKNOWLEDGMENTS

This research was supported in part by the NSF grant IIS-2232382. We thank Hamed Alimohammadzadeh for the drawings of the Dronevision presented in this paper and Rohit Bernard for the video recordings of circular Crazyflie flight patterns with different alignments.

REFERENCES

[1] Parastoo Abtahi, Benoit Landry, Jackie (Junrui) Yang, Marco Pavone, Sean Follmer, and James A. Landay. 2019. Beyond The Force: Using Quadcopters to Appropriate Objects and the Environment for Haptics in Virtual Reality. In *Proc. ACM CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3290605.3300589

[2] Hamed Alimohammadzadeh, Rohit Bernard, Yang Chen, Trung Phan, Prashant Singh, Shuqin Zhu, Heather Culbertson, and Shahram Ghandeharizadeh. 2023. Dronevision: An Experimental 3D Testbed for Flying Light Specks. In *The First International Conference on Holodecks* (Los Angeles, California) *(Holodecks '23)*. Mitra LLC, Los Angeles, CA, USA, 1–9. https://doi.org/10.61981/ZFSH2301

[3] Jonas Auda, Nils Verheyen, Sven Mayer, and Stefan Schneegass. 2021. Flyables: Haptic Input Devices for Virtual Reality Using Quadcopters. In *Proc. ACM Symposium on Virtual Reality Software and Technology*. Article 40, 11 pages.

[4] Peter Brooker. 2009. Simple Models for Airport Delays During Transition to a Trajectory-Based Air Traffic System. *The Journal of Navigation* 62, 4 (2009), 555–570. https://doi.org/10.1017/S0373463309990105

[5] Kuan-Wen Chen, Ming-Ru Xie, Yu-Min Chen, Ting-Tsan Chu, and Yi-Bing Lin. 2022. DroneTalk: An Internet-of-Things-Based Drone System for Last-Mile Drone Delivery. *IEEE Transactions on Intelligent Transportation Systems* 23, 9 (2022), 15204–15217. https://doi.org/10.1109/TITS.2021.3138432

[6] Yang Chen, Hamed Alimohammadzadeh, Shahram Ghandeharizadeh, and Heather Culbertson. 2023. Towards Enabling Complex Touch-based Human-Drone Interaction.. In *IROS Workshop on Human Multi-Robot Interaction* (Detroit, USA).

[7] Yuda Chen, Haoze Dong, and Zhongkui Li. 2023. Asynchronous Spatial Allocation Protocol for Trajectory Planning of Heterogeneous Multi-Agent Systems. arXiv:2309.07431 [cs.RO]

[8] Zhiyong Chen, Xiaoyuan Luo, and Bicheng Dai. 2017. Design of Obstacle Avoidance System for Micro-UAV Based on Binocular Vision. In *2017 International Conference on Industrial Informatics - Computing Technology, Intelligent Technology, Industrial Information Integration (ICIICII)*. 67–70. https://doi.org/10.1109/ICIICII.2017.87
[9] Halit Ergezer and Kemal Leblebicioğlu. 2014. 3D Path Planning for Multiple UAVs for Maximum Information Collection. *Journal of Intell Robot Syst* 73, 4 (2014), 737–762. https://doi.org/10.1017/S0373463309990105
[10] Nils Gageik, Paul Benz, and Sergio Montenegro. 2015. Obstacle Detection and Collision Avoidance for a UAV With Complementary Low-Cost Sensors. *IEEE Access* 3 (2015), 599–609. https://doi.org/10.1109/ACCESS.2015.2432455
[11] Shahram Ghandeharizadeh. 2021. Holodeck: Immersive 3D Displays Using Swarms of Flying Light Specks. In *ACM Multimedia Asia* (Gold Coast, Australia). ACM Press, New York, NY, 1–7. https://doi.org/10.1145/3469877.3493698
[12] Shahram Ghandeharizadeh. 2022. Display of 3D Illuminations using Flying Light Specks. In *ACM Multimedia*. ACM Press, New York, NY, 2996–3005.
[13] Bing Han, Tengteng Qu, Xiaochong Tong, Jie Jiang, Sisi Zlatanova, Haipeng Wang, and Chengqi Cheng. 2022. Grid-optimized UAV indoor path planning algorithms in a complex environment. *International Journal of Applied Earth Observation and Geoinformation* 111 (2022), 102857. https://doi.org/10.1016/j.jag.2022.102857
[14] Yu-Hsin Hsu and Rung-Hung Gau. 2022. Reinforcement Learning-Based Collision Avoidance and Optimal Trajectory Planning in UAV Communication Networks. *IEEE Transactions on Mobile Computing* 21, 1 (2022), 306–320. https://doi.org/10.1109/TMC.2020.3003639
[15] Hailong Huang, Andrey V. Savkin, and Chao Huang. 2021. Reliable Path Planning for Drone Delivery Using a Stochastic Time-Dependent Public Transportation Network. *IEEE Transactions on Intelligent Transportation Systems* 22, 8 (2021), 4941–4950. https://doi.org/10.1109/TITS.2020.2983491
[16] Yang Huang, Jun Tang, and Songyang Lao. 2019. Collision Avoidance Method for Self-Organizing Unmanned Aerial Vehicle Flights. *IEEE Access* 7 (2019), 85536–85547. https://doi.org/10.1109/ACCESS.2019.2925633
[17] Ravinder Kumar Jyoti, Mohit Kumar Malhotra, and Debasish Ghose. 2021. Rogue Agent Identification and Collision Avoidance in Formation Flights using Potential Fields. In *2021 International Conference on Unmanned Aircraft Systems (ICUAS)*. 1080–1088. https://doi.org/10.1109/ICUAS51884.2021.9476866
[18] Elia Kaufmann, Lennart Bauersfeld, Antonio Loquercio, et al. 2023. Champion-level drone racing using deep reinforcement learning. *Nature* 620 (2023), 982–987. https://doi.org/10.1038/s41586-023-06419-4
[19] Kostas Margellos and John Lygeros. 2011. Hamilton–Jacobi Formulation for Reach–Avoid Differential Games. *IEEE Trans. Automat. Control* 56, 8 (2011), 1849–1861. https://doi.org/10.1109/TAC.2011.2105730
[20] Kostas Margellos and John Lygeros. 2013. Toward 4-D Trajectory Management in Air Traffic Control: A Study Based on Monte Carlo Simulation and Reachability Analysis. *IEEE Transactions on Control Systems Technology* 21, 5 (2013), 1820–1833. https://doi.org/10.1109/TCST.2012.2220773
[21] Kenjiro Niwa, Keigo Watanabe, and Isaku Nagai. 2017. A detection method using ultrasonic sensors for avoiding a wall collision of Quadrotors. In *2017 IEEE International Conference on Mechatronics and Automation (ICMA)*. 1438–1443. https://doi.org/10.1109/ICMA.2017.8016028
[22] Kirtan Gopal Panda, Shrayan Das, Debarati Sen, and Wasim Arif. 2019. Design and Deployment of UAV-Aided Post-Disaster Emergency Network. *IEEE Access* 7 (2019), 102985–102999. https://doi.org/10.1109/ACCESS.2019.2931539
[23] Junayed Pasha, Zeinab Elmi, Sumit Purkayastha, Amir M. Fathollahi-Fard, Ying-En Ge, Yui-Yip Lau, and Maxim A. Dulebenets. 2022. The Drone Scheduling Problem: A Systematic State-of-the-Art Review. *IEEE Transactions on Intelligent Transportation Systems* 23, 9 (2022), 14224–14247. https://doi.org/10.1109/TITS.2022.3155072
[24] Junayed Pasha, Zeinab Elmi, Sumit Purkayastha, Amir M. Fathollahi-Fard, Ying-En Ge, Yui-Yip Lau, and Maxim A. Dulebenets. 2022. The Drone Scheduling Problem: A Systematic State-of-the-Art Review. *IEEE Transactions on Intelligent Transportation Systems* 23, 9 (2022), 14224–14247. https://doi.org/10.1109/TITS.2022.3155072
[25] Ryan R. Pitre, X. Rong Li, and R. Delbalzo. 2012. UAV Route Planning for Joint Search and Track Missions—An Information-Value Approach. *IEEE Trans. Aerospace Electron. Systems* 48, 3 (2012), 2551–2565. https://doi.org/10.1109/TAES.2012.6237608
[26] Georg Schildbach and Francesco Borrelli. 2016. A dynamic programming approach for nonholonomic vehicle maneuvering in tight environments. In *2016 IEEE Intelligent Vehicles Symposium (IV)*. 151–156. https://doi.org/10.1109/IVS.2016.7535379
[27] Joshua A. Shaffer, Estefany Carrillo, and Huan Xu. 2018. Hierarchal Application of Receding Horizon Synthesis and Dynamic Allocation for UAVs Fighting Fires. *IEEE Access* 6 (2018), 78868–78880. https://doi.org/10.1109/ACCESS.2018.2885455
[28] Hang Sun, Juntong Qi, Chong Wu, and Mingming Wang. 2020. Path Planning for Dense Drone Formation Based on Modified Artificial Potential Fields. In *2020 39th Chinese Control Conference (CCC)*. 4658–4664. https://doi.org/10.23919/CCC50068.2020.9189345
[29] Jiayi Sun, Jun Tang, and Songyang Lao. 2017. Collision Avoidance for Cooperative UAVs With Optimized Artificial Potential Field Algorithm. *IEEE Access* 5 (2017), 18382–18390. https://doi.org/10.1109/ACCESS.2017.2746752
[30] C. Tomlin, G.J. Pappas, and S. Sastry. 1998. Conflict resolution for air traffic management: a study in multiagent hybrid systems. *IEEE Trans. Automat. Control* 43, 4 (1998), 509–521. https://doi.org/10.1109/9.664154
[31] T. Williamson and N.A. Spencer. 1989. Development and operation of the Traffic Alert and Collision Avoidance System (TCAS). *Proc. IEEE* 77, 11 (1989), 1735–1744. https://doi.org/10.1109/5.47735
[32] Xiaojing Zhang, Alexander Liniger, and Francesco Borrelli. 2021. Optimization-Based Collision Avoidance. *IEEE Transactions on Control Systems Technology* 29, 3 (2021), 972–983. https://doi.org/10.1109/TCST.2019.2949540
[33] Wenxuan Zheng, Jin Xiao, and Tong Xin. 2017. Integrated navigation system with monocular vision and LIDAR for indoor UAVs. In *2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*. 924–929. https://doi.org/10.1109/ICIEA.2017.8282971
[34] Yaoming ZHOU, Yu SU, Anhuan XIE, and Lingyu KONG. 2021. A newly bio-inspired path planning algorithm for autonomous obstacle avoidance of UAV. *Chinese Journal of Aeronautics* 34, 9 (2021), 199–209. https://doi.org/10.1016/j.cja.2020.12.018