IEICE Communications Express, Vol.13, No.9, 389–392

ComEX

LETTER

A distributed UAV management system inspired by packet-switched networks

Takahiko Haraguchi[1, a], **Hiroshi Katada**[2], **Taku Yamazaki**[1], **Takumi Miyoshi**[1], **Ryo Yamamoto**[3], **and Kiyoshi Ueda**[4]

Abstract Unmanned aerial vehicles (UAVs) are expected to be used in various applications such as delivery services and sensing from airspaces in smart cities. In the future, UAV control systems must address a densely mixed environment comprising various services and users regardless of individuals or businesses. However, users cannot flexibly join or leave the system because of their centralized design. This letter proposes a distributed UAV management system inspired by packet-switched networks, to address dense UAV environments. The proposed system controls autonomous UAVs as packets in packet-switched networks. Each UAV flies along a path composed of links between ground beacon devices as routers. We analyzed the characteristics of the proposed system in dense situations using computer simulation. Simulation results indicate that the proposed system can handle numerous UAVs based on packet-switched networks.

Keywords: unmanned aerial vehicle, UAV control system, urban air traffic management, wireless sensor network
Classification: Navigation, guidance and control systems

1. Introduction

In future smart cities, various city services based on detection, prediction, and automation based on artificial intelligence technologies are expected to support our daily lives. Unmanned aerial vehicles (UAVs) are a promising technology for intelligent city services in city airspaces (e.g., delivery services, sensing, and disaster responses) [1].

UAVs are an effective solution for deploying city services from airspace because they can avoid restrictions owing to various factors, such as traffic congestion on the ground. To realize city-scale UAV deployment, many countries have been preparing environments and legal regulations for safely deploying various UAV services in city airspaces [2, 3]. In other words, actual deployment of UAVs in city environments is still in progress. If a full-scale UAV deployment occurs in the future, the management system must handle dense and diverse UAV environments. Additionally, the management system must handle not only large landing companies but also small operators and private users, opening the market for various UAV service providers.

This letter proposes a distributed UAV management system that autonomously controls UAVs using a wireless multi-hop network composed of ground beacon devices, inspired by packet-switched networks to cope with a dense UAV environment with a variety of users.

2. Related work

Low-altitude urban air traffic management was studied and standardized in several countries [4, 5]. As a representative example, unmanned aircraft system traffic management (UTM), which controls UAVs used by various operators, was standardized as a centralized management approach [6]. However, UTM is not feasible for the free and flexible participation of new operators and individual UAV users because it manages the flight information of UAVs in a centralized manner from various perspectives. This makes it challenging for new operators to consider using UAVs in the market and for individuals to fly UAVs easily.

Contrary to the centralized approach, distributed UTM, which controls UAVs without requiring full knowledge of airspace information, were also studied [7]. Particularly, flight path design and dynamic path planning were proposed for multiple operators in the distributed UAV management environment [8]. These studies primarily focused on flight path planning based on aggregated information through the internet. Therefore, they did not address UAV management mechanisms from the perspective of operator participation and data collection for airspace traffic management.

An autonomous flight method was proposed as a decentralized management approach [9]. This method realizes the route construction for UAVs based on a ground network with smart meters. In a ground network, smart meters (nodes) are classified based on whether they belong to densely populated areas. In this method, UAV flight paths are determined to avoid nodes in densely populated areas based on an ad-hoc routing algorithm. After flight path construction, UAV periodically communicates with the ground nodes and flies to the destination by following nodes on the constructed path. However, it does not focus on the design and analysis in which many UAVs fly because it primarily focuses on the UAV flight path selection algorithm. Therefore, interactions among UAVs during flight and the effects of an enormous

---

[1] Graduate School of Engineering and Science, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama-shi, Saitama, 337–8570, Japan
[2] Department of Communications and Computer Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169–8555, Japan
[3] Graduate School of Informatics and Engineering, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo, 182–8585, Japan
[4] College of Engineering, Nihon University, 1 Nakagawara, Tokusada, Tamuramachi, Koriyama-shi, Fukushima, 963–8642, Japan
[a] mf22101@shibaura-it.ac.jp

DOI: 10.23919/comex.2024XBL0101
Received May 23, 2024
Accepted June 25, 2024
Publicized July 9, 2024
Copyedited September 1, 2024

number of UAVs during flight must be considered.

3. Proposed method

This letter proposes a distributed UAV management system that realizes flexible and free participation of various operators, including individuals. The proposed system is inspired by packet-switched networks and autonomously controls UAVs using a wireless multi-hop network composed of beacon devices installed on the ground.

Figure 1 presents an overview of the proposed system. To realize decentralized flight control of numerous autonomous UAVs, the proposed system is inspired by a traditional packet-switched network model in computer networks that can handle an enormous number of packets in a decentralized manner. To apply the packet-switched network model to the UAV transportation network model, the proposed system treats UAVs as packets, ground beacon devices (e.g., smart meters) as routers, and neighbor relationships between ground beacon devices as links. Therefore, the proposed system can apply network routing to UAV flight path selection to relay UAVs using ground beacon devices via connections between ground beacon devices. Figure 2 presents the specifications of the components of the proposed system.

UAVs, acting as packets, move along links to their destinations by following ground beacon devices as routers. In the proposed system, UAVs play various roles (e.g., sensing, monitoring, and delivery) depending on services and operators. Each UAV can communicate with a ground beacon device, and is necessarily associated with a router. UAVs obtain next-hop router information from the associated routers.

Ground beacon devices, acting as routers, relay UAVs as packets to determine the next-hop router based on the routing tables. Similar to the approach described in [9], we assume the use of existing wireless networks whenever possible, such as smart meter networks commonly deployed in various cities for automating power meter readings and implementing home management systems, rather than relying on specialized beacon devices. The routing table stores the entries comprising the destination address, hop count, and next-hop router. Each router periodically sends a control message, which includes its routing table, to its neighboring routers to discover links along the UAV flight path. Upon receiving this information, routers update their routing tables. Each router r_i has a maximum queue length $q_{r_i}^{\max}$ that denotes the maximum number of available UAVs staying on the router.

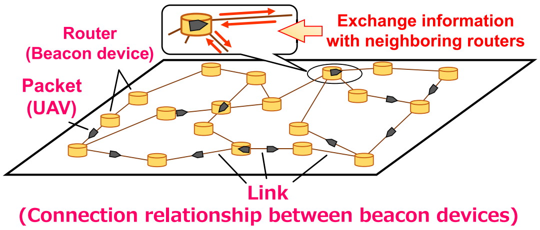


Fig. 1 Concept of the proposed method. Specifications of UAVs (packets), ground beacon devices (routers), and relationships between ground beacon devices (links) are illustrated in Fig. 2

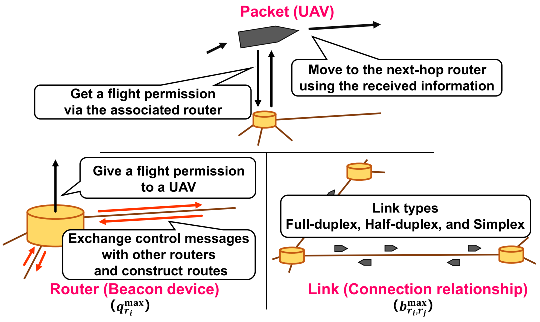


Fig. 2 Specifications of packet, router, and link in the proposed system.

The relationships between neighboring routers, which acting as links, can be utilized as UAV flight paths. We define three types of links: full-duplex, half-duplex, and simplex. A full-duplex link enables UAVs to fly simultaneously in both directions, a half-duplex link restricts UAVs to fly simultaneously in either direction, and a simplex link restricts UAVs to fly in a defined direction. Each link has maximum bandwidth $b_{r_i,r_j}^{\max}$, which denotes the maximum available number of flying UAVs on the link between r_i and r_j.

The procedure for a UAV p_i flying from a current-associated router r_i to a next-hop router r_j to travel to destination r_{dst} is as follows.

1. A UAV associated with r_i sends the information of the destination r_{dst} to r_i to request permission to fly to a next-hop router.
2. Upon receiving it, r_i obtains the information of next-hop router r_j for the destination r_{dst} from its routing table and sends a flight request to next-hop router r_j.
3. When r_j receives a flight request from the adjacent router r_i, it calculates the flight availability based on the total number of UAVs flying on all links from all adjacent routers to r_j and its current queue length, and then sends the availability to r_i.
4. Subsequently, r_i sends flight permission, including the next-hop router information r_j and its flight availability.
5. If the UAV receives flight permission, it starts moving to r_j. Otherwise, it waits for a certain period, and then returns to Step **1.**. Subsequently, if the UAV cannot obtain permission to fly to a next-hop router until a certain time, it makes an emergency landing in the safety area around r_i.

By repeating the aforementioned steps until the UAV arrives at its destination, the proposed system realizes autonomous decentralized UAV control. In addition, various existing network algorithms can be applied to the proposed system by taking inspiration from the packet-relaying model, such as the congestion control mechanism, to control UAV traffic.

4. Performance evaluation

We verified the performance of the proposed method by assuming multiple routers in a fixed area and simulating randomly flying UAVs in the area.

4.1 Simulation setup

Figure 3 illustrates the simulation topology. This simulation

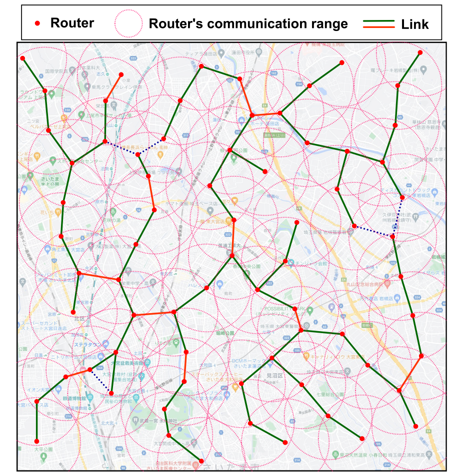


Fig. 3 Simulation topology based on the surrounding area around the Omiya campus, Shibaura Institute of Technology, Japan. We manually placed routers (red dots) within the area, ensuring that each router includes one node at least within the communication range. Additionally, we assigned links to routers based on their communication range. Links are categorized into two types based on the risk level when UAVs fall: those with low accident risks (green lines), which do not intersect with major roads, and those with high accident risks (red lines), which intersect with major roads.

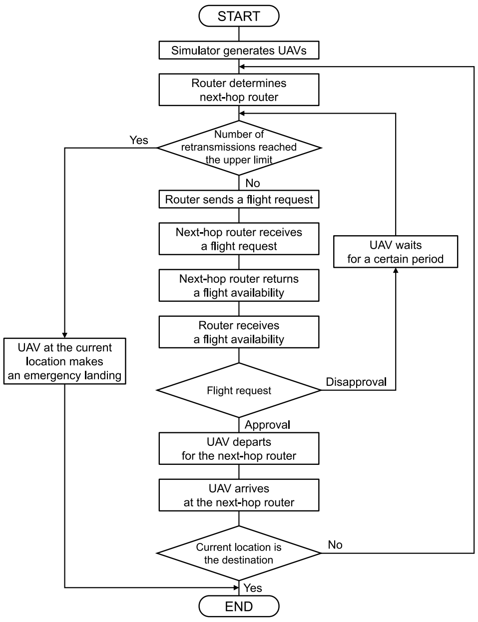


Fig. 4 Event flow during UAV flight in the simulation.

placed 72 fixed routers in an area of 5 km square on a map centered on the Omiya campus, Shibaura Institute of Technology, Japan. This simulation assumed that all flight links were full-duplex, and the routers constructed all paths to other routers in advance based on the shortest path first approach. The UAV flight time was calculated using the physical link length and flight speed based on Euclidean distance. Each control packet length was set to 50 bytes. Routers and UAVs had a 920 MHz-band wireless medium [10]. The transmission speed was set to 100 kbps, and the communication range was set to 500 m. The retransmission interval of the flight requests was set to 5 s and the maximum number of retransmission was set to 10.

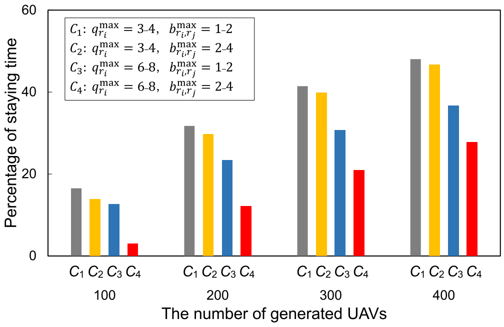


Fig. 5 Ratio of staying time on routers during flight.

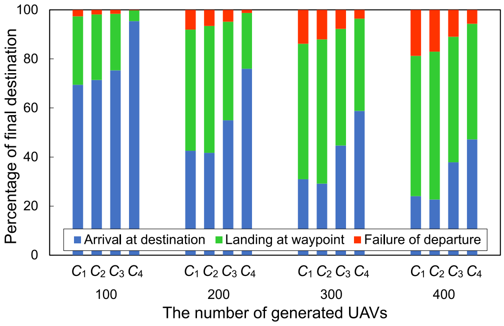


Fig. 6 Breakdown of the final destination of UAVs.

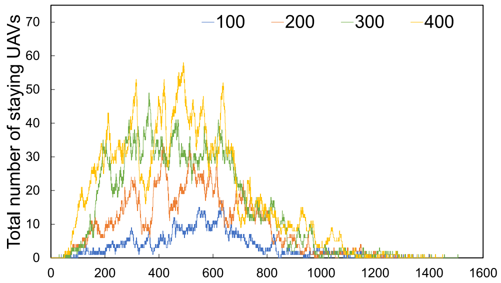
UAVs were randomly generated for 600 s, and their flight speed was set to 10 m/s. The departure and destination locations of each UAV were randomly determined, and they flowed based on the event flow shown in Fig. 4. The number of UAVs was changed from 100 to 400 to evaluate the impact of the UAV density. The energy consumption of UAVs was not considered since we currently focus on evaluating the fundamental behavior of the proposed system.

To consider the link capacity differences, we classified each link and changed its bandwidth $b_{r_i,r_j}^{\max}$ based on the presence of an intersection with a major road such as a railroad, national road, and highway, thereby indicating a risk level associated with crossing the road as an example of the link configuration. Additionally, we also classified each router and changed their maximum queue length $q_{r_i}^{\max}$ based on whether it had a link to such intersections. These values vary based on scenarios from C_1 to C_4. In C_1, $b_{r_i,r_j}^{\max}$ was set to one or two based on whether it intersects with a major road, and $q_{r_i}^{\max}$ was set to three or four based on whether it has a link that intersects with a major road. In addition, from C_1, C_2 doubles $b_{r_i,r_j}^{\max}$, C_3 doubles $q_{r_i}^{\max}$, and C_4 doubles both $b_{r_i,r_j}^{\max}$ and $q_{r_i}^{\max}$.

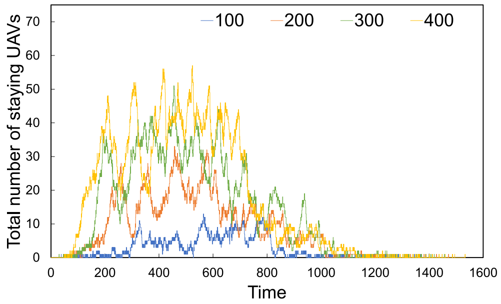
4.2 Simulation results

Figure 5 shows the percentage of staying time on routers during flight. The staying time increased significantly in all cases when the number of generated UAVs increased. On the other hand, when $q_{r_i,r_j}^{\max}$ and $b_{r_i,r_j}^{\max}$ increased, the staying time significantly decreased because more UAVs can simultaneously fly on each link.

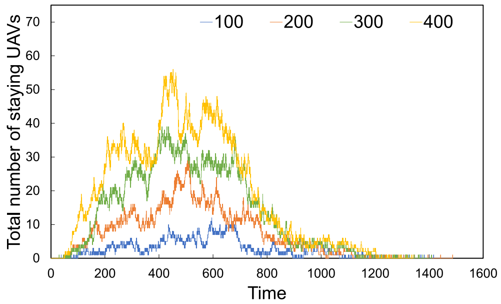
Figure 6 shows a breakdown of the UAV flight results. In dense environments, many UAVs cannot reach their destinations to land at relay routers and fail to fly from the source router. This is because the link utilization rate, queue



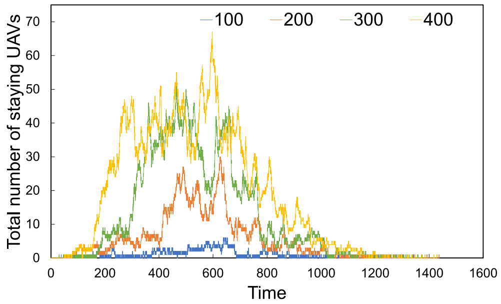
(a) C_1 ($q_{r_i}^{\max}$ = 3–4, $b_{r_i,r_j}^{\max}$ = 1–2)



(b) C_2 ($q_{r_i}^{\max}$ = 3–4, $b_{r_i,r_j}^{\max}$ = 2–4)



(c) C_3 ($q_{r_i}^{\max}$ = 6–8, $b_{r_i,r_j}^{\max}$ = 1–2)



(d) C_4 ($q_{r_i}^{\max}$ = 6–8, $b_{r_i,r_j}^{\max}$ = 2–4)

Fig. 7 Time transition of total number of UAVs staying on each router.

size, and staying time of the routers increase in dense environments. Hence, UAVs cannot depart from the source router or land at an intermediate router because flight to the next waypoint is not permitted. By increasing $q_{r_i}^{\max}$, $b_{r_i,r_j}^{\max}$, or both, more UAVs reached their destinations owing to the increased capacity of routers and links. Therefore, UAVs can avoid failing to depart from a source or land at an intermediate router. In other words, similar to existing packet-switched networks, we can autonomously improve the available bandwidth in the airspace to increase the queue size $q_{r_i}^{\max}$ and link bandwidth $b_{r_i,r_j}^{\max}$.

Figures 7(a)–(b) show the time variation of the total number of UAVs staying on routers according to the cases of C_1 to C_4. The results indicate that the total number of UAVs staying on routers increased when the number of generated UAVs increased. In addition, the number of UAVs staying on routers started to increase immediately after the start of the simulation because the proposed system constructed a single path between points of departure and destination. In other words, the current proposed system may concentrate UAVs in a specific airspace because it does not have a function of avoiding congested airspaces. Therefore, the proposed system needs to balance traffic in the airspace and alleviate congestion in a specific airspace by using a multi-path routing algorithm.

5. Conclusion

This letter proposed a distributed UAV management system using ground beacon devices and evaluated the proposed system through simulations. As future work, we aim to evaluate the proposed system under more practical scenarios and develop algorithms inspired by packet-switched networks from the perspectives of multi-path routing and congestion control.

Acknowledgments

This work was supported by JSPS Grant-in-Aid for Scientific Research JP24K14922.

References

[1] N. Mohamed, J. Al-Jaroodi, I. Jawhar, A. Idries, and F. Mohammed, "Unmanned aerial vehicles applications in future smart cities," *Technological Forecasting and Social Change*, vol. 153, pp. 1–15, April 2020. DOI: 10.1016/j.techfore.2018.05.004

[2] C. Stöcker, R. Bennett, F. Nex, M. Gerke, and J. Zevenbergen, "Review of the current state of UAV regulations," *Remote Sens.*, vol. 9, no. 5, pp. 1–26, May 2017. DOI: 10.3390/rs9050459

[3] I.L. Henderson, "Aviation safety regulations for unmanned aircraft operations: Perspectives from users," *Transport Policy*, vol. 125, pp. 192–206, Sept. 2022. DOI: 10.1016/j.tranpol.2022.06.006

[4] N.S. Labib, M.R. Brust, G. Danoy, and P. Bouvry, "The rise of drones in internet of things: A survey on the evolution, prospects and challenges of unmanned aerial vehicles," *IEEE Access*, vol. 9, pp. 115466–115487, Aug. 2021. DOI: 10.1109/ACCESS.2021.3104963

[5] R. Shrestha, I. Oh, and S. Kim, "A survey on operation concept, advancements, and challenging issues of urban air traffic management," *Frontiers in Future Transportation*, vol. 2, pp. 1–20, April 2021. DOI: 10.3389/ffutr.2021.626935

[6] "ISO 23629-5 UAS traffic management (UTM) –part 5: UTM functional structure," ISO 23629-5:2023, pp. 1–14, April 2023.

[7] U.-J. Lee,, S.-J. Ahn, D.-Y. Choi, S.-M. Chin, and D.-S. Jang, "Airspace designs and operations for UAS traffic management at low altitude," *Aerospace*, vol. 10, no. 9, pp. 1–22, Aug. 2023. DOI: 10.3390/aerospace10090737

[8] N.S. Labib, G. Danoy, J. Musial, M.R. Brust, and P. Bouvry, "Internet of unmanned aerial vehicles–A multilayer low-altitude airspace model for distributed UAV traffic management," *Sensors*, vol. 19, no. 21, pp. 1–22, Nov. 2019. DOI: 10.3390/s19214779

[9] K. Ueda and T. Miyoshi, "Autonomous navigation control of UAV using wireless smart meter devices," *J. Telecommun. Inform. Tech.*, vol. 2, pp. 64–72, July 2019. DOI: 10.26636/jtit.2019.132319

[10] T. Okabe and K. Kobayashi, "An overview of electric smart meter system and example approaches to technical subjects," *J. Soc. Instrument and Control Engineers*, vol. 57, no. 9, pp. 623–628, Sept. 2018. DOI: 10.11499/sicejl.57.623