Evacuation Guidance System Using UAVs of Multiple Types at Disaster

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***Abstract*—Unmanned Aerial Vehicles (UAVs) have undergone rapid advancements in performance and affordability, resulting in their widespread availability and increased attention for their potential use in the field of disaster relief. UAVs are specifically employed for confirming the extent of damage in disaster situations and providing guidance to evacuees. Many existing systems have assumed to leverage UAVs to control their movements based on disaster information, e.g., fire and building collapse, collected from ground-based sensor devices. However, in scenarios where sensor devices are damaged during disasters, collecting disaster information is difficult, rendering effective disaster relief support unfeasible. Additionally, the limited battery capacity of UAVs poses a constraint for prolonged continuous operation. Therefore, in this paper, we propose an evacuation guidance system that facilitates large UAVs in searching for evacuees while simultaneously transporting small UAVs. Once evacuees are located, the small UAVs are separated to provide evacuation guidance to evacuees, eliminating the need for coordination with ground sensor devices and enabling long-duration and wide-area operation. Using a computer simulator, we confirm the effectiveness of the proposed system.**

***Index Terms*—UAV; Evacuation; Disaster relief;**

I. INTRODUCTION

In Japan, earthquakes and tsunamis account for an extremely high percentage of disasters in the world due to natural conditions such as topography, geology, and weather. In the Great East Japan Earthquake of 2011, tsunami, tidal wave, caused extensive damage, so it is necessary to construct ways to mitigate the damage caused by earthquakes and tsunamis. In recent years, UAVs (Unmanned Aerial Vehicles) have attracted a wide attention to relief disasters due to their rapidly evolving capabilities, low cost, and wide availability. In particular, UAVs can easily gather information on inaccessible and dangerous areas to confirm the widespread distribution of damage conditions in large-scale disasters. For gathering information at large-scale disasters, although crewed aircraft have a much longer flight distance and flight time, manned aircraft are limited in terms of number of aircraft, deployment, and take-off/landing locations. By using UAVs to collect information in areas that cannot be fully surveyed by manned aircraft, it is expected that disaster relief operations can be conducted more safely and efficiently.

For this reason, there have been many studies on disaster relief using UAVs, and many existing researches assumed that UAV operations are controlled based on information obtained from IoT devices on the ground [1]. However, it is difficult to collect accurate disaster information in a large-scale disaster when the communication infrastructure is disrupted due to damage to base stations, or when IoT devices are damaged by fire or collapsed buildings. On the other hand, UAVs can provide evacuation guidance even when IoT devices in disaster areas cannot be used. However, UAVs have limited flight time limitations due to the battery capacity of UAVs. Therefore, in this paper, we propose a new evacuation guidance system in which a large UAV equipped with a petrol engine carries a small UAV while searching for evacuees. After finding evacuees, the large UAV separates the small UAV to provide evacuation guidance or sends evacuation routes to a mobile terminal owned by evacuees, without requiring coordination with IoT devices. We propose a new evacuation guidance system that can be used over a long period of time and over a wide area, without requiring coordination with ground based IoT devices. Using a computer simulation, we evaluate the evacuation completion time and the number of people who have completed the evacuation when using the proposed system. Section II describes the related works, and section III describes the proposed method in detail. Section IV presents the numerical evaluation results, and Section V concludes this manuscript.

II. RELATED WORKS

A. Development of large UAVs

Most battery-powered UAVs used for logistics and surveying have a short flight time of only about 30 minutes and require many spare batteries when used for long periods in the field. To solve these problems, hybrid UAVs with engine generators and batteries have been developed [2] [3]. The power generated by engine generators is used for motors, so long endurance operations is possible. The payload of cameras and sensors can be changed according to the application, and the payload weight is much larger than that of conventional small UAVs.

B. Detection of people on the ground from aerial images

In [4], a system for real-time detection of people from images and videos taken by UAVs was developed and the results were visualized on a GIS platform. The authors also evaluated the accuracy of the person position estimation calculated from the images and assessed the performance of the person detection algorithm for images taken from different altitudes. Using the collected images, a custom binary classifier based on Haar-like features was trained to classify human or non-human, thereby reducing computational time. The system can identify a person within a few seconds from an image taken at an altitude of 40 meters.

C. Investigating road conditions and creating evacuation routes using UAV

In [5], Liu et al. proposed to detect road conditions from multispectral images captured in real time by the multispectral camera of a UAV or downloaded in advance from a satellite. The roads extracted from the images can be used to create evacuation routes. The system also estimates the walking speed of pedestrians using a combination of road surface materials and weather information and weights the evacuation routes to create the best evacuation routes for people.

D. Utilization of large and small UAVs

In [6], Cai et al. proposed a novel search-task-oriented UAV system that combined a large fixed-wing UAV and a small rotary-wing UAV to efficiently execute missions. The large UAV equipped with a small UAV thoroughly searched the target area based on a pre-planned trajectory, and the large UAV released the small UAV after the search target was found. The released small UAV can obtain detailed information by searching at a low altitude, and simulation results showed that the proposed system has great potential for application in search missions. Moreover, in [7], Nauwynck et al. developed a system that enabled the aerial separation of two coupled UAVs using commercially available small UAVs. By attaching a winch system consisting of servo motors, the mother UAV can lower the child UAV to an arbitrary release altitude. It was shown that the child UAV can be easily separated from the mother UAV in mid-air by leaving the mother UAV at a distance where it was not affected by the turbulence generated below.

E. Guidance of evacuee by small UAVs

In [1] [8] [9], an agent-type evacuation action support system was developed to support rapid evacuation guidance by coordinating and linking IoT devices such as UAVs, sensors, and mobile terminals according to the situation. The UAV agent searched for hazardous areas and created an evacuation plan to avoid secondary disasters. The evacuation routes were created based on the distance to secondary disasters such as fire, tsunami height, time, etc. Once the evacuation routes were established, a UAV equipped with evacuation signs flied autonomously to guide the evacuation.

F. Provision of disaster information to mobile devices

In [10], Fujihara et al. proposed a disaster evacuation guidance system assuming unforeseen failure of the mobile communication infrastructure due to natural disasters. By using DTN communication between mobile phones and sharing disaster information through epidemic routing, the proposed system quickly proposed evacuation routes based on real-time information about impassable roads. Numerical evaluation using road map graphics showed that the average evacuation time can be significantly reduced by using DTN communication.

G. Communication between UAVs and mobile terminals on the ground

In [11], Sato et al. proposed a disaster information communication system using a message ferry that simultaneously transmitted disaster information from a UAV having disaster information to disaster victims. In this system, the node delivery rate to ground terminals was evaluated by simulation when the altitude of the message ferry was 20, 30, or 40 meters, and the size of the transmitted data was 0.5, 1, or 3 Mbytes. The numerical results confirmed that when all ground terminals were stationary, data delivery was successful for any combination of flight altitude and data size, and that highly reliable information delivery was possible.

III. Proposed Method

A. Issues When Using UAVs in Disasters

Although several studies have proposed evacuation guidance support systems using UAVs and mobile terminals in disasters, there are several issues that need to be addressed. In [12], UAVs were used for evacuation guidance with assuming that AR markers were attached with evacuees to accurately capture their location information. However, it was difficult to guide evacuees who were not wearing AR markers. Another problem was the low penetration rate of the AR markers that were assumed to be used. In [1] [8] [9], the authors developed systems enabling evacuation guidance considering secondary disasters such as fires and blocked roads due to collapsed houses by autonomously linking UAVs and IoT devices based on disaster information collected from IoT devices installed in the city. However, because the system relied on IoT devices installed on the ground to collect disaster information, it was difficult to operate the system if the devices were damaged during a disaster. In addition, the small battery capacity of the commercially available battery-powered small UAVs expected to be used in both cases, so the maximum flight time was only about 30 minutes. The actual flight time was even shorter because of the power consumed by searching for evacuees and exchanging information between UAVs. UAV-based evacuation guidance systems must be able to operate UAVs even if sensor equipment on the ground was damaged during a large-scale disaster, and the impact of flight time limitations due to UAV battery capacity must be minimized.

B. Evacuation Guidance System Using Large UAVs, Small UAVs, and Mobile Terminals

In order to solve the above problems, we propose to search for evacuees in disaster areas and guide them by combining two types of UAVs, i.e., large rotorcraft UAV and small rotorcraft UAV, and mobile terminals such as smartphones owned by evacuees. In the proposed system, a large UAV equipped with a small UAV flies over disaster areas along a predetermined search path and searches for evacuees. The disaster situation on the ground is grasped from the images of the ground surface taken during the flight, and a safe evacuation route is calculated considering the places that cannot be accessed due to fire or collapse. When an evacuee is detected, the created evacuation route is transmitted to the evacuee's smartphone or other mobile terminal if communication between the large UAV and the mobile terminal of the evacuee is possible.

When communication with the terminal is not possible, the small UAV is released from the large UAV, and the small UAV guides the evacuee. In the experiment of [11], when the UAV is operated as a message ferry, and 3 Mbytes of data is transmitted from the UAV flying at an altitude of 100 meter at a speed of 10 km/h to multiple smartphones on the stationary ground, the probability of successful delivery for all terminals is more than 95%. In this paper, we assume that 3 Mbytes data can be transmitted to mobile terminals of evacuees from the large UAV with using IEEE802.11g as wireless communication protocol. When the UAV detects a disaster victim with active mobile terminal, it hovers 50 meters above the disaster victim and transmits information of the evacuation route to the mobile terminals of the disaster victim. The use of a large UAV with a petrol engine is expected to increase the flight time compared to a small UAV, allowing a continuous search for evacuees over a larger area. In addition, since information about the ground surface is obtained from images taken by the large UAV, appropriate evacuation guidance is possible even if sensor equipment installed on the ground is damaged.

C. Assumptions

In this section, we describe some technical assumptions to realize the proposed method. All of these conditions can be achievable based on the techniques described in Section II. From [2] [3], it is possible for a large UAV to fly autonomously carrying a small UAV. Literature [7] shows that it is possible to separate a small UAV from a large UAV in the air. As shown in [4], we can detect people from the images taken by the UAV, and we can determine the disaster situation on the road surface from the images taken by the UAV and determine the evacuation route based on the obtained disaster situation [5]. In [8] [9], a small UAV is actually used to guide evacuees. In [11], it is shown that the communication between UAVs and mobile terminals works without any problems. In this study, we evaluate the proposed method by creating simulations based on the assumption that these technical conditions are feasible.

D. Procedures of Proposed Method

The detailed procedures of the proposed method are shown below.

1) The large UAV creates the search route covering the entire disaster area without omission.
2) The large UAV takes off from the relief base station (BS) with a small UAV on board.
3) The large UAV flies over the disaster area along the predefined search path.
4) The large UAV extracts roads from images captured during the flight, identifies and records areas that are impassable due to fire or collapsed houses.
5) If an evacuee is detected, the large UAV derives the shortest route between the location of detected evacuee and the evacuation site, based only on passable roads. If a safe evacuation route to the evacuation site cannot be derived, the UAV continues to fly along the search path until an evacuation route can be derived.
6) The large UAV will attempt to derive an evacuation route at regular intervals, and if an evacuation route can be derived, it will move into the airspace above the evacuees.
7) After passing over the evacuees, the large UAV transmits the evacuation route to the mobile terminal of the evacuees if they are available or separates the small UAV from the large UAV if the evacuees do not have available mobile terminals.
8) When the small UAV is separated from the large UAV, the small UAV starts evacuation guidance by flying with the evacuees.
9) After completing the guidance for evacuees, the small UAV returns to the BS.
10) If the large UAV separates the small UAV, it returns to the BS, refuels, reloads the small UAV, and moves to the search resumption point to resume the search for evacuees.

The above steps are repeated until all evacuees have been evacuated to the evacuation point. If the fuel level of the large UAV drops below a certain level during the flight, the large UAV will return to the BS, refuel, and search for evacuees.

IV. Performance Evaluation

A. Evaluation Conditions

In this section, we evaluate the effectiveness of the proposed method by reproducing the operation of a large UAV and a small UAV by computer simulation. Open map data provided by OpenStreetMap (OSM) is used for realistic evacuation guidance. OSM data is expressed in XML format and consists of three basic elements: nodes, ways, and relations. Nodes define specific points on the ground by latitude and longitude, with some nodes representing intersections. A way is an ordered set of nodes defining a continuous line segment. Some ways contain road type tags that distinguish major roads from minor roads. Some ways are treated as individual roads and some nodes are treated as intersections. Relations define logical and geographical relationships between elements, such as directional constraints. The 2 km square area centered on the evacuation center is defined as the disaster area. The map data of the above area is obtained from the OSM, and we create a road network consisting of nodes representing intersections and paths representing roads. From this network, several nodes are randomly deleted to create a post-disaster road network.

Figure 1(a) shows the assumed disaster area, and Figure 1(b) shows the road network in this area. Moreover, Figure 2(a) shows the post-disaster road network. By deleting arbitrary nodes and the roads connected to them, we create roads that are impassable due to fire or house collapse. The nine red nodes around the evacuation center are defined as evacuation center nodes. Evacuees are allowed to evacuate if they can reach any of the shelter nodes from any node. Figure 2(b) shows an example of evacuee placement, and the yellow nodes in the figure are the initial location of evacuees. The initial locations of evacuees are randomly selected from the nodes of the post-disaster road network. The affected area is divided into four regions of equal area, and the number of evacuees in each region is chosen so that the number of evacuees in each region is equal. However, we exclude the cases where evacuees cannot evacuate to shelters to confirm the effectiveness of the proposed method. Isolated nodes are excluded from the initial placement of evacuees because it is impossible to construct an evacuation route connecting evacuees and evacuation centers.

In the computer simulation, we use four large UAVs, and each large UAV is assigned to each of the four areas, and each large UAV searches evacuees in each assigned area. After taking-off, the large UAV flies along a pre-defined search path to look for evacuees. The search path should be a flight path that can capture images of the entire disaster area without missing anything on the ground surface. Assuming that the field view of the optical camera of large UAV is 90 degrees, the area that can be photographed from above is the product of the horizontal distance and the vertical distance, which is twice the altitude of the UAV. If the altitude of the large UAV is 50 meters, the horizontal and vertical width distances are 100 meters. Figure 3 (a) shows the field of view of the large UAV, and Figure 3 (b) shows the effective detection range of the ground surface by the large UAV. In the simulation, a radius of 50 meters centered on the large UAV is considered as the area in which the large UAV can take pictures, for the sake of simplicity. The effective detection range is a radius of 40 meters.

Figure 4 shows the search flight paths of four large UAVs. Each UAV is responsible for each of the assigned 1,000 meter square area and flies according to a search path in which the search area expands outwards with the BS in the center. The distance between search paths is set at 50 meters to ensure that the disaster area is searched without gaps. If a node with an evacuee is detected by a large UAV for three consecutive seconds, the large UAV judges that the evacuee has been found and moves to the airspace above the evacuee. Then, depending on the communication status with the mobile terminal of evacuee, the evacuation route is transmitted, or evacuation guidance is provided by a small UAV separated from the large UAV. The evacuees do not move from the node where they are initially located until they are found by the large UAVs. The flight speed of the large UAVs is 20 km/h when flying the search path and 60 km/h when returning to the BS to reload the small UAV. The speed of movement of the small UAV and the evacuee during the evacuation is assumed to be 4 km/h. In an actual evacuation, the evacuees follow the small UAV, but in the simulation, it is assumed that the small UAV and the evacuees share location information and move simultaneously to simplify the process.

The number of evacuees to be deployed is E, the number of nodes to be removed from the road network is D, and the percentage of evacuees with a mobile device capable of communication is P. The number of evacuees is set to E = 32, and 10 patterns of node removal and 10 patterns of evacuee placement are generated for each of the numbers of nodes D = 70, 100 and 130, and the evacuation completion time is measured for each combination of these patterns, giving a total of 100 placement patterns. The initial location of the evacuees is selected from the nodes common to each post-disaster road network in each of the 10 node deletion patterns.

To evaluate the effectiveness of the proposed method, we compare the time required for completing evacuation of all evacuee among three methods. We define method X as the proposed method which judges the damage to the road on the ground from images taken while searching for evacuees and guides evacuees whenever it finds them. Moreover, we define method Y as the case without damages on ground sensor devices, and the large UAVs can determine the damage of roads on the ground before it starts searching for evacuees and guides evacuees whenever it finds them. Finally, we define method Z as the case in which the large UAVs start to guide all the found evacuees after completing the searches of all areas in the disaster area without omission and the identifications of the location of evacuees and impassable points.

(a) Disaster-Affected Area (b) Road Network

Fig. 1. Affected Areas and Road Network

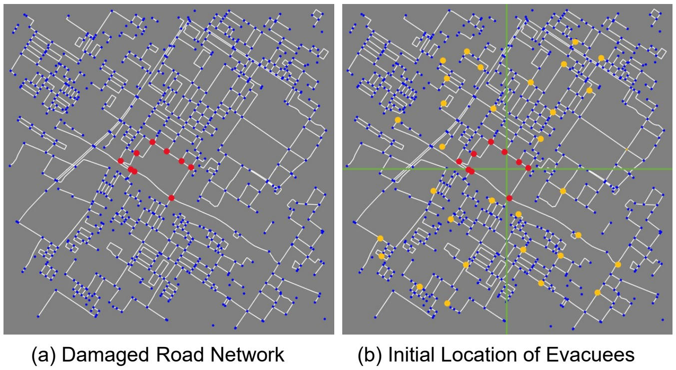

Fig. 2. Damaged Road Networks and Evacuee Deployment.

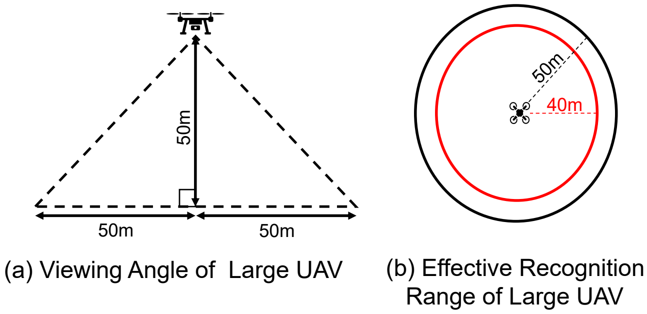

Fig. 3. Viewing Angle and Recognition Range of Large UAVs

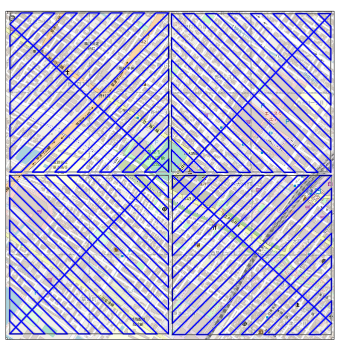

Fig. 4. Search flight paths for large UAVs

B. Cumulative Distribution of Evacuation Completion Times

Figures 5(a) to 5(c) show the cumulative distribution of evacuation completion times at $D = 70$ for $P = 0$, $P = 50$ and $P = 100$. In all cases, the evacuation completion time decreased in the order of method Y, method X, and method Z. Method Y had a shorter evacuation completion time than method X because all nodes have been discovered when an evacuee was found, and there were fewer cases where an evacuation route cannot be derived when an evacuee was found. The time to complete the evacuation was distributed after 5,000 seconds in method Z. As P increased, the graph shifted to the left and the time to complete the evacuation became shorter. This was because the probability of communicating with the mobile terminals of evacuees increased when the evacuee was found, and the number of times the UAV returned to the BS to reload the separated small UAV decreased.

Figures 6(a) to 6(c) show the cumulative distribution of evacuation completion times for $D = 100$, and as in the case of $D = 70$, the evacuation completion time decreased in the order of method Y, method X, and method Z in all cases. As P increased, the curves shifted to the left and the evacuation completion time decreased. Figures 7(a) to 7(c) show the cumulative distribution of evacuation completion times for $D = 130$. In this case, as in the $D = 70$ and $D = 100$ cases, the evacuation completion time decreased in the order of method Y, method X, and method Z. As P increased, the curves shifted to the left, and the evacuation completion time decreased.

The distribution range of the evacuation completion time decreased as D increased. This is because the probability of an evacuee being placed at a node far from the shelter decreased as D increased, and an increase in D had no effect on reducing the evacuation completion time. For all D, the evacuation completion time decreased in the order of methods Y, X, and Z. We confirmed that the overall evacuation completion time decreased as the proportion of evacuees with a mobile device capable of communication increased. In all cases D, the proposed method achieved almost the same evacuation time as the method with known obstacle locations, i.e., method Y, so we confirmed the effectiveness of the proposed method in simultaneously searching for evacuees and obstacle locations using large UAVs.

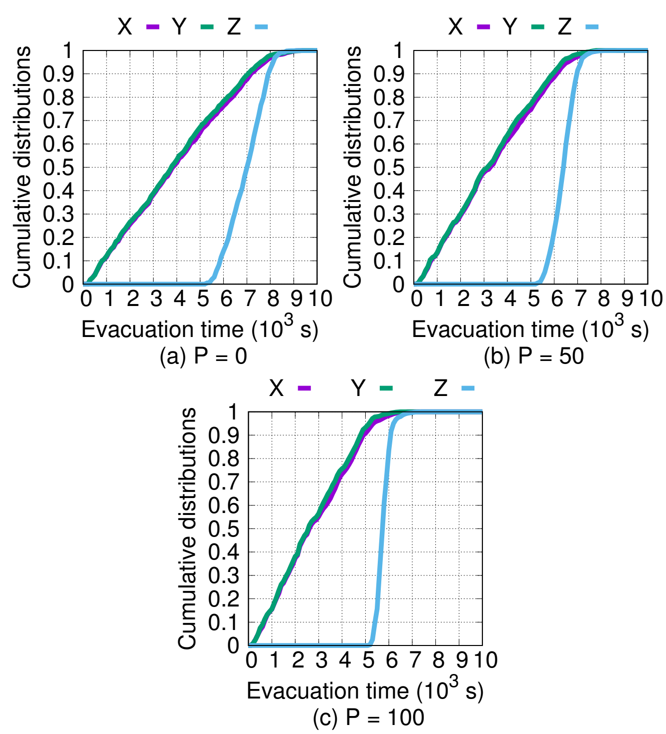

Fig. 5. Cumulative distribution of evacuation time when $D = 70$

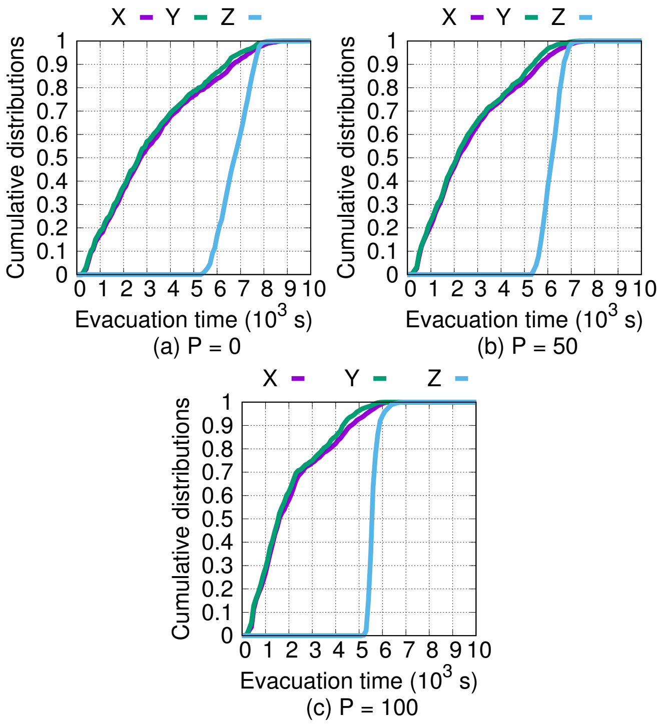

Fig. 6. Cumulative distribution of evacuation time when $D = 100$

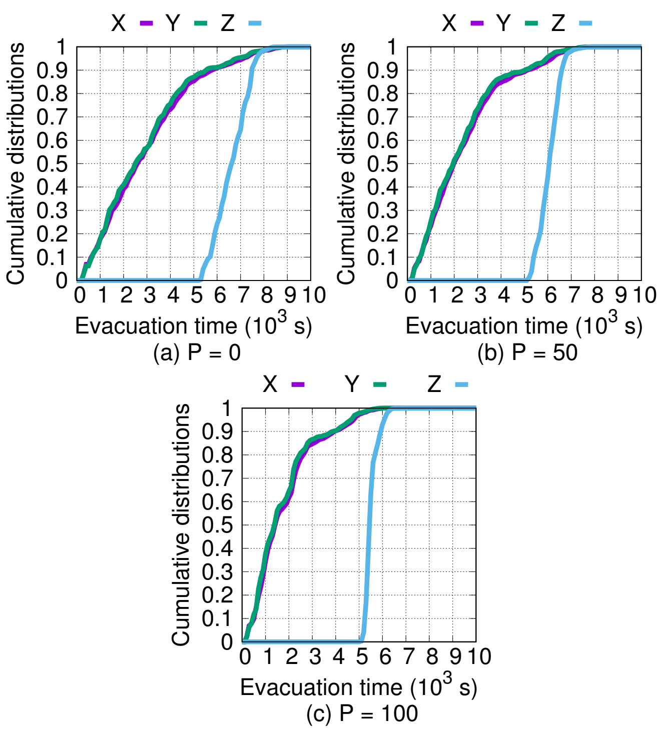

Fig. 7. Cumulative distribution of evacuation time when $D = 130$

V. Conclusion

The use of UAVs is attracting attention as a means of assessing damage distribution and conditions, establishing radio networks as temporary cell phone base stations, and guiding evacuees to evacuation centers. However, most battery-powered UAVs have low capacity, making long-term operation difficult. In addition, when UAVs rely on sensor equipment on the ground, it becomes difficult to complete proper disaster relief if the equipment is damaged. In this paper, we propose an evacuation system that combines multiple types of UAVs and mobile terminals owned by evacuees. The advantages of the proposed system can be summarized as follows.

- The use of large UAVs with gasoline engines enables long-term evacuation guidance over a wide area.
- Since the large UAV evaluates road damage based on images and video, it can be operated even if ground-based sensor equipment is broken. In addition, the system can provide evacuation guidance to all evacuees in the same amount of time regardless of the presence or absence of sensor equipment on the ground.
- A small UAV will provide evacuation guidance each time an evacuee is detected. Compared to the case where guidance is started after searching the disaster area and determining the location of evacuees and impassable areas, the proposed system takes shorter time to complete the evacuation of all evacuees.

In the future, we plan to evaluate the performance of the proposed system when the number and location of BSs and evacuation centers are changed. Moreover, we will investigate the method of optimally allocating BSs as well as search routes of large UAVs.

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