Electric-Vehicle-based Ad Hoc Networking and Surveillance for Disaster Recovery

Proposal of Three-Dimensional Mobile Surveillance Using Electric Helicopters

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Abstract—**In this paper, we argue that small electric vehicles (mini-EVs) may become increasingly prevalent in the future, leading to the realization of the so-called ubiquitous EV society. EVs have the potential to be a great resource for recovery from large-scale disasters. Specifically, each EV can be equipped with wireless communication devices, and so EVs in a disaster area can link together to form an EV-based mobile ad hoc network (EVANET). Two use cases of EVANET are emergency networks and disaster area surveillance. Focusing on the latter application, we present the concept of three-dimensional mobile surveillance (3DMS). In 3DMS, EVs on the ground cooperate with small lightweight unmanned electric helicopters (mini-EHs) to cooperatively collect information about the disaster area. Each EV and mini-EH pair is equipped with cameras and other sensors to monitor disaster damage. We present an effective method of solving the problem of limited continuous flying time of EHs. We investigate the requirements for a mini-EH in 3DMS. In particular, we demonstrate that autonomous piloting is necessary. To support autonomous piloting, we propose that EH position information be obtained using GPS and a low-power wireless transmission system between the mini-EH and the corresponding EV. We call this system the EH positioning system. Based on real-world experiments, we show that a prototype of the EH positioning system has adequate capabilities in terms of both transmission range and energy consumption.**

Keywords-ad hoc network; disaster; electric vehicle; helicopter; GPS

I. INTRODUCTION

The Great East Japan Earthquake and the resulting tsunami on March 11, 2011, caused severe disruption in both the telecommunications and power supply networks [1]. In the fixed telephone system (NTT-East), 18 telecom buildings were destroyed and 23 were flooded, 90 transmission routes were disconnected, 1,000 telecom buildings were powered off and 300 ceased to operate owing to a shortage of fuel for generating electric power, and 1.5 million subscriber lines became unusable. In the cell phone networks (NTT DoCoMo, KDDI, and Softbanks), 12,000 base stations ceased to operate (mostly because of commercial power failures and consequent battery power shortage), and the traffic regulation ratios were 70–95% and 30% for voice and mail, respectively. After the occurrence of the earthquakes and the tsunami over a wide area of East Japan, telecom companies made remarkably continual efforts to repair the disrupted buildings, facilities, and equipment in order to restore their services under the harsh conditions. However, the resources of the telecom companies were very limited in comparison with the scale of the damage caused by the disaster. Depending on their location, the population of the affected areas had either no communication services or disrupted services for days, weeks, or even months after the earthquake.

Today, environmental destruction and global warming have become serious concerns. Thus, there is an urgent worldwide need for the evolution of low-carbon sustainable societies. Automobile exhausts have been, and continue to be, a major cause of air pollution, but the markets for emission-reducing hybrid cars and electric vehicles (EVs) have experienced significant growth recently. EVs are an ideal exhaust-free means of minimizing air pollution in large cities, and they are expected to become increasingly popular as their associated costs continue to decrease. Further, in both developing and advanced nations, small one- or two-seater EVs (mini-EVs) are attracting attention as economical vehicles for use in communities, and it is expected that they will become increasingly prevalent in the near future. A further advantage of such vehicles is that they can provide mobility to the elderly, many of whom find regular walking difficult, so mini-EVs are an attractive proposition for aging societies.

When a large-scale disaster occurs, the first priority is to recognize the nature and scope of the disaster damage over the affected area in order to most effectively begin rescue and disaster recovery activities. The efficiency of activities such as surveying the damage, discovering survivors, and saving lives, however, is reduced by the lack of information on the disaster area owing to the destruction of and damage in the communications infrastructure and prolonged confusion in telecommunications services, as mentioned earlier. There is an urgent need to establish a more effective way of quickly providing a temporary communications and surveillance network over a large disaster area.

In this study, which assumes a growing market penetration by EVs in the near future, a novel approach for efficient networking and surveillance over a wide disaster area is presented. In our proposal, EV-based mobile ad hoc networking is used to rapidly deploy a communications network in the disaster area. A key player in our proposed system is the unmanned electric helicopter (EH). EVs and EHs are cooperatively employed to perform surveillance activities within the disaster area, allowing three-dimensional mobile surveillance (3DMS). There are many studies on applications of unmanned aerial vehicles (UAVs) including helicopters [2]-[14]. Some of these are targeted at disaster surveillance. However, the potential and benefits of EHs for use in wide-area disaster surveillance have not been fully explored.

Our main contributions are as follows: 1. The novel idea of cooperatively using EVs and unmanned EHs for wide-area disaster surveillance. 2. An effective method of solving the significant problem of limited continuous flying time of EHs. 3. The prototype of a feasible EH positioning system for autonomous piloting. The rest of this paper is organized as follows: Section II describes the usefulness of ad hoc networks using EVs to provide emergency communication networking in disaster areas. Section III presents the concept of 3DMS using EVs and EHs, with an analysis of the availability of EHs for airborne surveillance. Section IV describes not only the EH positioning system to support autonomous piloting but also the prototype development and initial experimental results. Finally, Section V offers our conclusions.

II. AD HOC NETWORKS USING ELECTRIC VEHICLES DEPLOYED IN DISASTER AREAS

A. Background

The electric vehicle (EV) is considered an attractive alternative to the gasoline-powered car as a means of reducing air pollution caused by automobile exhaust gases. With the objective of replacing gasoline-powered cars with electric ones, major automobile manufacturers have been developing EVs whose production costs and continuous driving ranges are comparable with those of conventional automobiles powered by gasoline engines. Although these goals have not yet been fully achieved, the EV market has recently experienced significant growth.

A very small EV with one or two seats, which we call a mini-EV (see the specifications of mini-EVs in [15]), is another promising development, which in the near future may be popular in communities regardless of issues of air pollution from CO_2 emissions. Mini-EVs are cheaper to purchase or maintain and require smaller parking spaces, allowing households to possess them as their first car or as additional cars. They are also ideal for B2B and B2C delivery services in communities. They have further uses, especially in an aging society. It has been reported that cars driven by elderly drivers typically carry only one or two passengers, and the distance driven each day is relatively short, conditions that are well matched by the limited capabilities of current EVs. Unlike a gasoline-powered vehicle, an EV has no mechanical engine and requires little maintenance, which is convenient for the elderly. Gasoline-powered vehicles must also be refueled at gas stations, which can be a burden on an elderly driver. In contrast, a mini-EV can be powered at home or solely by a solar battery mounted on the roof, thereby eliminating the time needed to attend a gas station. These features significantly reduce the burden of vehicle maintenance on the elderly.

A serious problem in many communities is the inconvenience caused by changes in public transportation services, such as where the frequency of a bus service is reduced or cancelled on routes that are unprofitable. In this context, the availability of mini-EVs in a community becomes important. A personal EV may be conveniently used to support personal mobility for daily activities such as shopping and visiting others in the neighborhood, particularly for the aged who may have difficulty walking. Thus, personal EVs can improve the quality of life (QOL) for the elderly and contribute to the realization of a vibrant community. Mini-EVs will potentially create a new EV market in the near future, achieving significantly greater penetration in the community to fashion what in this paper is referred to as the ubiquitous EV society. The battery capacity of an EV, even a mini-EV, is not comparable to that of the battery in a gasoline-powered car. An improvement in the energy density of batteries is further expected. The ubiquitous EV society will be one of ubiquitous large-capacity batteries, which will additionally prove to be useful during any prolonged blackout following on from a large-scale disaster.

B. EV-based Ad Hoc Networks

Communications after large-scale disasters and between cars have been considered major applications in the research and development of mobile ad hoc networks (MANETs) [16]. With regard to car-to-car communication, the vehicular ad hoc network (VANET) [17] has been studied particularly within the framework of intelligent transport systems (ITS). A vehicle is equipped with a communication device, allowing the vehicle to act as a communication station to form a MANET with other vehicles. The presence of gasoline-powered vehicles is implicitly assumed in VANET research, and the applications of a VANET while the vehicle is driven are of major interest. With its increasing penetration, however, the mini-EV can become a principal player in the formation of a VANET. An EV-based ad hoc network is called an EVANET [15]. It is noteworthy that an EV can operate as a communication station for a long time by using its large-capacity battery, regardless of whether it is moving or stationary, whereas a gasoline-powered vehicle cannot provide the same utility when its engine is switched off. Consequently, EVANET applications need not be limited to situations where the vehicle is being driven, but may be enhanced to provide new services when the vehicle is parked. For example, suppose that mini-EVs in individual household parking spaces at night form an EVANET within a community. In such a scenario, the EVANET might act as a sensor network to detect or prevent crimes such as burglary.

C. Use Cases for Disaster Recovery

In the ubiquitous EV society, a tremendous number of EVs may be in use by a community. When a disaster occurs, many of these may be utilized for disaster recovery. Mini-EVs owned by public offices and those volunteered by individuals can be deployed to form an EVANET. In order to

TABLE I. ALTERNATIVES FOR SURVEILLANCE FROM THE AIR IN COOPERATION WITH MINI-EVS

	Mobility	**Hovering**	**Wind resistance**	**Operation time**	**On-EV charging**	**Logistics**
Tethered balloon	No	Yes	Limited	Fair	Feasible	Full backup needed
Airship	Low	Yes	Limited	Fair	Difficult	Full backup needed
Helicopter	Low	Yes	Fair	Limited	Feasible	Light support needed (electric helicopter)
Airplane	High	No	Fair	Limited	Difficult	Full backup needed

reach a position suitable for networking, a mini-EV can take advantage of its small body to pass through narrow routes while avoiding any obstacles created by the disaster. Two major applications of EVANETs are presented below.

1) Emergency network: When telecommunications services are degraded or disrupted by traffic congestion or damage to network facilities, an EVANET can function as a secondary telecommunications infrastructure (emergency network) throughout the affected area. Forming an EVANET can drastically shorten the network construction time compared to conventional methods. The surplus battery power available can be remotely monitored using the EVANET itself, and mini-EVs whose batteries have been exhausted can easily be replaced with others whose batteries are fully charged. Such emergency networks can be used for rescue purposes, damage surveying, and communicating with people in shelters [18]. The higher their antennas are located, the greater the probability that a line-of-sight (LOS) exists between two communication stations. A longer transmission range is also expected because of the decrease in radio reflection from the ground. For reasons of wind resistance and driving safety, a 10-m-high antenna cannot be used on an EV while it is being driven. However, a high antenna can be used when the EV is parked. Specifically, an elastic pole fixed vertically to the car body can be used to support an antenna mounted on its top. This pole can be retracted and carried by the EV while it is driven. The experimental results show that a higher antenna can extend the transmission range owing to the increase in the line-of-sight range and the decrease in radio reflection from the ground. The throughput of a 9-m-high antenna is significantly greater and more stable than that of a 2-m-high antenna [19].

2) Disaster area surveillance: An EVANET can function as a surveillance infrastructure in a disaster area. In addition to its communication device, each EV is equipped with cameras and sensors for collecting information on the affected area. The information collected by each EV is delivered through the EVANET to the data collection station, where an Internet gateway is available. It is thus possible for a disaster recovery headquarters to efficiently and quickly obtain basic information over a wide disaster area in order to acquire an overview of the damage to allow for an effective allocation of rescue and recovery resources.

III. THREE-DIMENSIONAL MOBILE SURVEILLANCE

A. Surveillance from the Air

By deploying a number of EVs in the disaster area, it is possible to achieve mobile surveillance that is both extensive and efficient. In addition, airborne surveillance is considered an effective way to efficiently obtain a complete view of a disaster area [11]-[14]. By combining the surveillance results from the air and ground, improvements in the coverage, accuracy, and efficiency of the surveillance can be expected.

The various means of airborne surveillance are listed and qualitatively evaluated in Table I. The airship, helicopter, and airplane can be either manned or unmanned for piloting. The former is costly and the availability of human pilots is limited. In this paper, the latter is investigated. The tethered balloon and airship have relatively little wind resistance, since both use bladders inflated with helium gas for lift. In the case of the tethered balloon, it is necessary to bring helium gas bottles to the site for inflating or refilling the balloon, for which the balloon needs to be brought to the ground and then released again. The surveillance coverage is limited, but a power source is not required, allowing for relatively lengthy surveillance [20]. The airship allows extensive flying and hovering over the disaster area, but fuel is necessary for flying and continuous operation time is limited by both the decrease in gas pressure and the fuel consumption. The helicopter has characteristics in common with the airship, but fuel consumption is greater and continuous operation time is further limited. Due to its flight characteristics, the airplane has difficulty both in continuously monitoring the same area and in adapting its route according to the situation. Like the helicopter, its continuous operation time is limited by its fuel consumption. As the power source for flying, an engine using a fuel such as gasoline or a motor with a battery may be considered, but the appropriate choice is necessarily based on the application requirements. A motor can be selected if the helicopter or airplane is small and light and a relatively short continuous operation time is acceptable. The need for a human pilot on the ground should be avoided by means of autonomous piloting, which allows for a longer period of continuous operation. Since a battery is necessary to provide the energy source for mounted cameras and communication devices, its capacity is also a limitation on continuous operation time. Such constraints need to be carefully balanced at the design stage with respect to continuous operation time.

Each method requires support services such as the supplementing of helium gas or engine fuel and battery charging for a motor or communication device. In mobile surveillance, where a large number of EVs are deployed within the disaster area, an EV on the ground can be used as a base station for battery charging (on-EV charging). On-EV charging can easily be used for a tethered balloon or a helicopter. In the case of a very small EH, the roof of an EV can be used as the heliport and the battery of the EH can then be charged from the battery of the EV. An airship is considerably bigger than a tethered balloon and requires a relatively large space for landing, and an airplane needs a runway for takeoff and landing, while a tethered balloon needs periodic topping-up of its helium gas. These supports are unnecessary for an EH owing to on-EV charging.

B. System Concepts

Based on the qualitative evaluation of the possibilities of airborne surveillance in Section III.A, we have chosen the EH for our system. The proposed surveillance system is thus composed of EVs, including mini-EVs, and tiny unmanned EHs (mini-EHs). In the proposed system, each EV also functions as the carrier of a mini-EH. That is, each EV is equipped with a mini-EH on its roof for the deployment, takeoff, and landing of the mini-EH. Moreover, the EV provides charging from its battery to that of the mini-EH. The EVs and mini-EHs are equipped with cameras and sensors used for surveillance. These unique features differentiate the proposed system from existing approaches [11]-[14]. This system is referred to as a three-dimensional mobile surveillance (3DMS) system. The smallest configuration of the 3DMS system is a single pairing of an EV and an EH. Many EVs and EHs, however, are required to participate in cooperation for the surveillance of a large disaster area. In principle, the pairing between EVs and EHs is fixed, but more flexible pairing relations can also be considered. For example, some EVs may perform surveillance without their partner EHs, or may cooperate with and provide charging to EHs other than their partner.

To minimize the total weight of the mini-EH, the weight of the battery for its motor is strictly limited, which means that the battery capacity is also limited, allowing only for a relatively short continuous flight. However, a mini-EH can engage in airborne surveillance repeatedly, owing to on-EV charging. A carrier EV may be equipped with a fast charger to shorten the charging time. In addition, a carrier EV can be equipped with spare EH batteries. By substituting a spare EH battery for the spent battery of the landed mini-EH, the waiting time of the mini-EH on the heliport of the EV is shortened. The spent EH battery from the mini-EH is recharged on the EV in preparation for reuse. The driver of the EV is typically someone who cannot manually pilot the corresponding mini-EH. Autonomous piloting of the mini-EH should thus be supported in principle.

It is possible to view the entire disaster area from the air. A mini-EH can monitor from the air locations that an EV cannot access owing to a lack of roads or the presence of obstacles, and from there can then take pictures and search for survivors. EVs and mini-EHs form a mobile ad hoc network and share the information collected by each EV and mini-EH, delivering such information to a data collection station. When two EVs are out of transmission range with each other, a mini-EH in the air can be used as their relay node or message carrier [21].

TABLE II. REQUIREMENTS FOR MINI-EH IN 3DMS

Mini-EH Features	Required Values
Size (Length and width)	Less than 1 m
Mass	1–3 kg
Maximum altitude	100–200 m
Maximum speed	50–60 km/h
Payload	500–1000 g
Continuous flying time	No less than 15 min
Wind resistance	6 m/s
Rain resistance	10 mm/h
Remote-control range	200–1000 m

C. Requirements

Based on the system concepts given in Section III.B, the requirements for a mini-EH in 3DMS are summarized in Table II.

A mini-EH can be remotely piloted through the use of commands (simple piloting). Specifically, the following functions should be supported:

- Takeoff and ascent to the designated altitude
- Hovering at the designated altitude and position
- Landing from the current position
- Progressing or retreating, sliding right or left, and ascending or descending at the designated speed and time
- Turning right or left with the designated angle
- Circuitous flight around the designated position with the designated speed

In addition, autonomous piloting should be supported for a mini-EH. Some examples of autonomous piloting are as follows:

- Landing on the heliport on the roof of the corresponding carrier EV
- Flying at the same altitude, direction, and distance from the carrier EV
- Returning to the takeoff location and landing when communication with the carrier EV is lost
- Returning to the carrier EV and landing before the battery is spent

The development of a piloting system that meets the above requirements is beyond the scope of this paper.

D. Availability of EH for Airborne Surveillance

As mentioned in Section III.B, a mini-EH can fly continuously for a relatively short time due to its limited battery capacity, and the on-EV charging time may be considerably longer than the continuous flying time, resulting in a low availability, which is defined as the ratio of the total flying time to the total surveillance period. By using spare batteries, the availability can be improved. Without loss of generality, we assume that the mini-EH consumes a single battery for each flight. Let n be the total number of

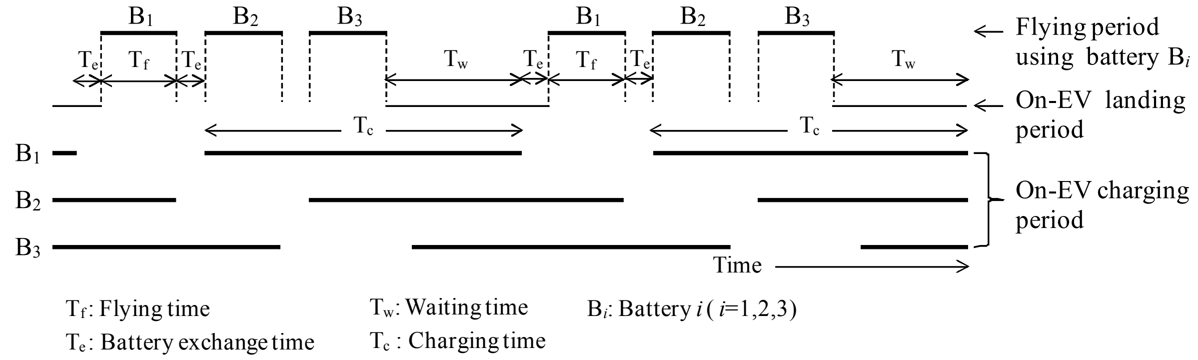

Figure 1. Rotation of charging and use of batteries for EH flying.

batteries, including spare batteries. In the example of Fig. 1, three batteries are used in rotation, where the ith battery B_i ($i = 1, 2, 3$) is used during the flying periods marked by B_i in the upper part of the figure, and is charged on the EV during the periods marked by B_i in the lower part of the figure. The following relation is easily obtained from Fig. 1:

$$\begin{aligned} T_w &= T_c - (n-1)T_f - (n-2)T_e & \left(n < \frac{T_c + T_f + 2T_e}{T_f + T_e}\right) \\ &= 0\ . & (Others) \qquad (1) \end{aligned}$$

The availability, A, is then given by the following equation:

$$\begin{aligned} A &= \frac{nT_f}{T_c + T_f + 2T_e} & (T_w > 0) \\ &= \frac{T_f}{T_f + T_e}\ . & (T_w = 0) \qquad (2) \end{aligned}$$

A numerical example is given in Fig. 2, where the availability versus the total number of EH batteries n are shown for three different charging times T_c: 15, 30, and 60 min, assuming that T_e = 1 (min) and T_f = 15 (min). The availability increases with increasing n and becomes saturated when n reaches and exceeds its minimum required value; at this point, the mini-EH does not need to wait for the on-EV charging to be completed, and maximum availability is obtained. It is shown that the waiting time and the total number of batteries are in the trade-off relation, and relatively fewer EH batteries are sufficient to obtain the maximum availability under practical assumptions.

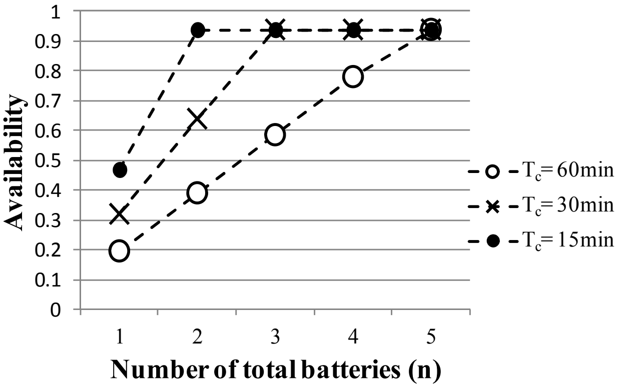

Figure 2. Number of total batteries.

IV. EH POSITIONING SYSTEM TO SUPPORT AUTONOMOUS PILOTING

A. Basic Approach

Most EH products in the market support simple operator-controlled piloting and some partly support the autonomous piloting mentioned in Section III.C. There are two approaches to autonomous piloting for 3DMS. In the first approach, autonomous piloting is developed on the basis of existing products. In the second approach, autonomous piloting is developed independently of the existing products. We adopt the second approach because we want to develop an autonomous piloting system that can be applied to any EH product, allowing the user to select an appropriate EH product for 3DMS from many candidates. In the proposed method, the basis of the autonomous piloting is to recognize the current positions of the mini-EH and the partner (carrier) EV, which is responsible for piloting the mini-EH (and is thus referred to as the piloting EV). To this end, both the mini-EH and the EV are equipped with GPS receivers. The GPS measurement data are periodically transmitted from the mini-EH to the partner EV. A similar method was also used for managing the formation flight of unmanned aerial vehicles (UAVs) in [8]. However, our system and prototype are both optimized to our application in terms of transmission range and the maximum speed and payload of the mini-EH. The mini-EH controller on the EV compares the GPS data history of the mini-EH with that of the EV and sends appropriate commands to guide the mini-EH toward the desired position. In order to realize such autonomous piloting, the EV needs to have functions to periodically collect GPS data from the mini-EH. We call this system the EH positioning system.

The transmission range of the radio system used for the

EH positioning system should be designed sufficiently greater than that of the one used for remotely piloting the mini-EH. When the mini-EH happens to wander beyond its remote-control range, the carrier EV can still receive position data from the mini-EH. According to the requirements given in Section III.C, the mini-EH should be designed to land on the site when it has lost control from the piloting EV. The mini-EH continues to periodically transmit location messages so that the piloting EV can easily search for the lost mini-EH. In this sense, the EH positioning system is independent of the remote-piloting mechanism of the mini-EH, in accordance with the aforementioned second approach, which is more reliable than the first approach.

B. System Components

The EH positioning system is composed of a tag mounted on the mini-EH and a base station in the partner EV. An EH-tag is composed of a CPU, GPS receiver, barometer, radio transceiver, antenna, memory, and battery (see Fig. 3). The GPS receiver in the EH-tag periodically performs a measurement and the GPS data are transmitted to the base station on the EV. To reduce the battery consumption of the EH-tag, a license-free low-power transmission system with a maximum transmission power of 10 mW is used for data transmission from the EH-tag to the base station on the EV. We expect that when the EH is in flight, the GPS measurements by the EH-tag are always successful, line-of-sight is maintained between the EH-tag and the base station, and the measured GPS data can be successfully transmitted to the base station.

A base station includes a communication module, micro server, memory, and router. The communication module (see Fig. 4) is used to receive GPS data sent from the EH-tag. The base station is connected to the mini-EH controller on the EV (see Fig. 5). It is also equipped with various sensors, including a camera, weather sensor, and barometer to monitor the surroundings of the EV.

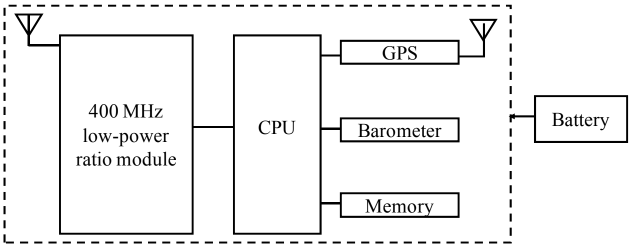

Figure 3. Functional blocks of an EH-tag.

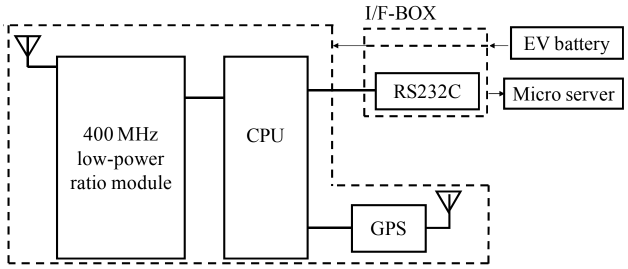

Figure 4. Functional blocks of the communication module of a base station on an EV.

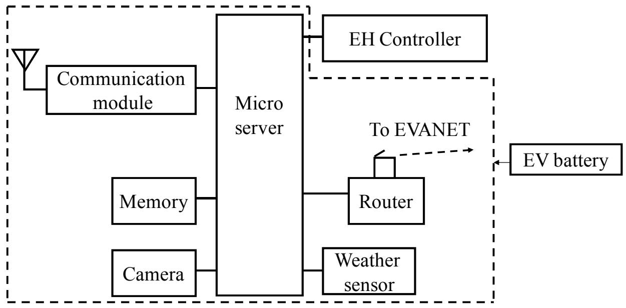

Figure 5. Functional blocks of a base station on an EV.

C. Power-Saving Mechanism

The mini-EH controller on the EV periodically sends status information, such as flying/landing status and flying speed, of the EH to the base station. The base station in turn determines the frequency of GPS measurements and sends it to the EH-tag. For energy conservation, GPS measurements in the EH-tag are periodically performed only when in the flying state. The measured GPS data and the barometer readings are subsequently sent to the base station. The base station periodically updates the period of GPS measurements. If a pre-determined number of consecutive updates are not received, the pre-determined minimum period is configured in the EH-tag.

The frequency of the GPS measurements during the flight of the mini-EH should be configured to detect a change of distance between the mini-EH and the piloting EV of the order of 10 m flown at the maximum relative speed. When it is 10 m/s, the frequency should be set to around once per second. This frequency may be dynamically configured to decrease, reflecting the normally lower speed of the mini-EH, so that energy consumption may be minimized.

Figure 6. The case and IC motherboard developed for an EH-tag.

TABLE III. SPECIFICATIONS OF COMPONENTS FOR EH-TAG

Components	Size (mm)	Mass (g)
IC motherboard	96 × 50 × 0.8	10.5
Case	110 × 53 × 49	33
Lithium-thionyl chloride battery	*Φ14.5 × 24.5*	9
GPS antenna	3.2 × 1.6	0.9
Radio antenna	*Φ5.5*	0.9
GPS module	15 × 12.5	1.1
Microcomputer	17×17	0.5
Resistor, condenser	1.0×0.5	Not measurable

D. *Prototype Development*

We developed prototypes of the EH-tag and base station mentioned in Section IV.B. The main challenge was the development of a small lightweight EH-tag that can be mounted on the mini-EH. A picture of the developed EH-tag is shown in Fig. 6, and the specifications of the components selected for the EH-tag are listed in Table III. The total mass is about 60 g, which meets the mini-EH payload limit of the requirements in Table II. We used only existing products for the components of the developed EH-tag. Further reductions in size and weight can be expected by using components designed specifically for the EH-tag.

E. *EH-tag Battery Lifetime*

A small lightweight battery that is capable of operating at 3 V and of the order of 10 mA is necessary as the energy source of the EH-tag. To meet this requirement, a lithium-thionyl chloride battery with a capacity of 1,100 mAh was selected. To estimate the lifetime of the battery used for the EH-tag, we conducted experiments in which GPS measurements were performed every minute and the measurement data were transmitted to the base station each time the measurement succeeded. Based on the results of the experiments, the battery lifetime is about 31 h. The current draw is highest, at 45 mA, during GPS measurements. Assuming that a GPS measurement is conducted every second in the worst case, as mentioned in Section IV.C, and that the current draw is constant at 45 mA, the calculated lifetime of the EH-tag battery is about 24 h. It is also expected that the GPS measurements will stop or slow down, as mentioned in Section IV.C. Considering these factors, which reduce the energy consumption, the EH-tag can be expected to work continuously for at least one whole day without the need for recharging or replacement, which is well suited to a 3DMS application.

F. *Real-World Data Delivery Experiments*

We conducted experiments to verify the transmission range of the EH positioning system by using the base stations on the Niigata University campus and in Sawata on Sado Island (see Fig. 7). GPS measurements were performed by the EH-tag every 1 min for 10 min at each distance from the base station and at each height from 20 m to 100 m above the ground in 20 m steps. Unlike our objective of using EH-tag on the EH, we used a balloon to hold the EH-tag in the air at each height in this experiment, because a prototype EH was not ready at that time. It is worth noting that a similar data delivery performance would be obtained when the EH-tag is actually mounted on a mini-EH. The measured GPS data were sent to the base station. As expected, there were no failures in GPS measurements. The average data transmission success ratios are shown in Fig. 8. It is observed that a data transmission success ratio of almost 100% was achieved at both sites for distances up to 6 km. However, there were examples of the case in which the transmission is unsuccessful even though the distance is relatively short. We surmise that these failures occur when the EH-tag posture is changed due to the balloon swinging in the wind.

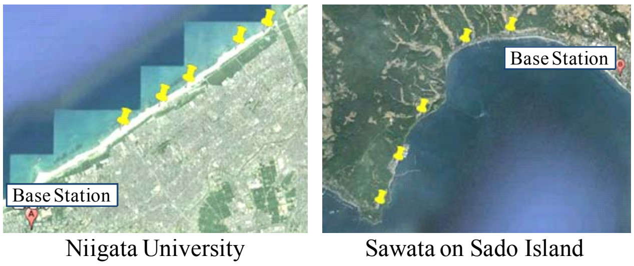

Figure 7. Experimental sites.

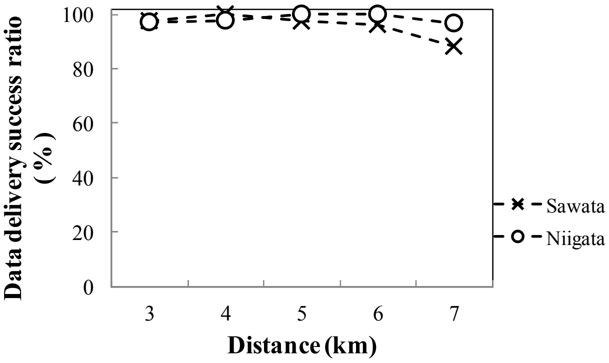

Figure 8. Data delivery success ratios for the EH positioning system.

Thus, it has been confirmed that the EH positioning system has sufficient data transmission range, significantly exceeding the remote piloting range of the mini-EH, and can be applied to 3DMS.

V. CONCLUSION AND FUTURE WORKS

In this paper, we argued that small electric vehicles (mini-EVs) may be increasingly common in the future, leading to the realization of the so-called ubiquitous EV society. In the future, these EVs can be a great resource for recovery from large-scale disasters. Specifically, where each EV is equipped with wireless communication devices, a number of EVs available in a disaster area can form EV-based mobile ad hoc networks (EVANETs). Two use cases of EVANET are emergency networks and disaster area surveillance. Focusing on the latter application, we presented the concept of three-dimensional mobile surveillance (3DMS). In 3DMS, the EVs on the ground cooperate with small lightweight unmanned electric helicopters (mini-EHs) to collect information on the disaster area. Each EV and mini-EH pair is equipped with cameras and other sensors to monitor damage arising from the disaster. We gave an effective method of solving the problem of the limited continuous flying time of EHs. We investigated the requirements for a mini-EH in 3DMS. In particular, we pointed out that autonomous piloting is necessary. To support autonomous piloting, we proposed that EH position information be obtained using the GPS and a low-power wireless transmission system between the mini-EH and the corresponding EV. We call this system the EH positioning system. Based on real-world experiments, we showed that a prototype of the EH positioning system has adequate capabilities in terms of transmission range and energy consumption.

Future works include resolving the EV positioning problem in a large disaster area, autonomous creation of EH flight routes based on the position of a partner EV, the assignment of surveillance work among EVs and their partner EHs, performance evaluation of surveillance data collection, and the development of a prototype of the autonomous piloting system for 3DMS in order to demonstrate the feasibility of the 3DMS on the basis of real-world experiments and performance evaluations.

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