Wide Area Surveillance Using Limited-Flying-Time Helicopters

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Abstract—**Sensor networks can be useful for disaster recovery. It is essential how to realize time-efficient and pervasive surveillance over a wide disaster-affected area. A surveillance architecture based on collaboration among multiple electric helicopters is presented. Area division principles are used considering cost minimization as well as considering the requirements of allowable surveillance time, and transmission range and effective bandwidth of the wireless link. A simple model and methodology for area division considering the battery-capacity-limited flying range are presented. Numerical examples show the feasibility of the area division approach.**

Keywords-disaster; surveillance; ad-hoc network; wireless; electric vehicle.

I. INTRODUCTION

Information and Communication Technology (ICT) can contribute to the creation of disaster-resilient societies in two ways. One way is to increase the resilience and tolerance of communication infrastructure toward disasters. Second way is to develop new ICT technologies for promoting disaster recovery activities. In this study, we focus on use of ICT for surveillance of wide areas such as disaster-affected areas.

A disaster, such as big earthquake, hurricane, etc. can affect quite a large area, e.g., as large as 100 km square. It would take enormous time to perform close, detail, and pervasive surveillance to cover the entire area and deliver the obtained surveillance results in real-time to the remote disaster recovery headquarter. It is thus essential how to realize time-efficient and pervasive surveillance over a wide disaster-affected area.

Surveillance can be performed on the ground or from the air. The latter provides a wider field of vision than the former, and is, therefore, especially efficient when the disaster-affected area is wide. For realizing aerial surveillance, a single aerial vehicle such as air plane or helicopter can be used to cover the entire disaster-affected area. However, this solution may not be acceptable since it would take much time to complete one-round surveillance for a large area due to speed limit of the aerial vehicle. Furthermore, it is also a problem how to deliver the obtained surveillance results to the disaster recovery headquarter in real-time and continuously. An alternative approach using a number of very small Unmanned Aerial Vehicles (UAVs) with fixed or rotary wings is attractive from the viewpoints of the investment required and operational ease. Indeed, this approach can be applied in various applications including surveillance and forms an active research area [1]-[16]. Multiple UAVs working in parallel may be required for monitoring a wide area. An approach called "three-Dimensional Mobile Surveillance (3DMS)," was proposed in [15], where multiple Electric Vehicles (EVs) and very small, lightweight unmanned UAVs with rotary wings (helicopters), termed "Electric Helicopters (EHs)," were cooperatively engaged in surveillance over a wide area.

The contributions of this paper are as follows:

1) A time-efficient and pervasive surveillance architecture based on the collaboration of multiple EHs, each with its partner EV, is presented.

2) Area division principles are given based on cost minimization, as well as considering requirements of allowable surveillance time and transmission performance.

3) A simple model and methodology for area division devised by considering the battery-capacity-limited flying range are presented.

The remainder of this paper is organized as follows:

Section II summarizes related works. Section III discusses surveillance strategies for designing wide-area surveillance architectures. Section IV outlines the basic approach and surveillance architecture of the proposed system. Section V presents a surveillance area division scheme, and Section VI presents numerical examples. Finally, the conclusions of this paper are presented in Section VII.

II. RELATED WORK

There exist many studies on Vehicular Ad hoc NETworks (VANETs) [17]. In these studies, vehicles with engines consuming fuels such as oil and gas were assumed implicitly, and applications useful during driving were extensively explored and developed. The benefits of using EVs in a disaster-affected area for providing emergency communication networks have been discussed [18].

UAVs can be used for improving the connectivity and performance of ad hoc networks on the ground [8]-[10]. It is easier to control UAV position in air given the lack of obstacles or physical boundaries. Therefore, UAV relay positioning methods have been studied extensively [11]-[14].

When multiple UAVs work in tandem for surveillance in a disaster-affected area, inter-UAV coordination for task assignment and responsibility is essential to improve surveillance efficiency. Coordination among helicopter UAVs for forest-fire surveillance was explored; here, the focus was on observing the fire's expanding perimeter and devising a parallel, non-overlapping, uniformly time-consuming patrolling task assignment method [6]. In disaster surveillance, all areas should be monitored continuously, and repeatedly. This problem has not been fully discussed in the previous works.

III. SURVEILLANCE STRATEGY

A. Ground-based vs. Air-based

Ground-based surveillance is indispensable for close, detailed, and pervasive surveillance, as well as the subsequent rescue activities. Rescue team members should be equipped with means of transportation such as vehicles that enable them to quickly move around the wide area within limited time. In addition to surveillance using ground vehicles, surveillance can be performed from the air. It is easier to view the entire disaster-affected area from the air. Aerial vehicles can monitor locations that ground vehicles cannot access owing to a lack of roads or the presence of obstacles.

B. Manned vs. Unmanned

Aerial vehicles can be either manned or unmanned. The former type is expensive, and the availability of human pilots is limited. Focusing on UAVs, the need for a human pilot on the ground should be avoided. In principle, the UAV can fly and work through autonomous piloting or remote automatic control by computer without human manual operation.

C. Fuel vs. Electricity

Both ground vehicles and UAVs can be powered by fuel oil or electricity. The use of EVs and electric UAVs is attractive in the disaster recovery phase because their batteries can be recharged using local power generation facilities such as solar panels, even under long blackouts, whereas fuel-based vehicles and UAVs cannot be refueled under a shortage of oil stock in a disaster-affected area. Focusing on UAVs, the spare battery can be immediately substituted for the spent battery, while it takes some time to refuel the oil tank.

D. Supply of EV

EVs can reduce the air pollution due to automobile exhaust gases. The EV market has recently experienced significant growth.

Moreover, a very small EV with one or two seats, called a mini-EV, can potentially grow EV market in the near future, achieving significantly greater penetration in the community, especially in aging societies [18]. In such an environment, in the event of a large-scale disaster, it would be easy to divert EVs available in the community toward disaster recovery activities, thus reducing the reserves required for disaster recovery. Therefore, the supply of EVs for disaster recovery is expected economically feasible.

E. UAV options

UAVs include airships, helicopters, and airplanes. Airships allow for relatively long flying and hovering times over the disaster-affected area, which are desirable for continuously monitoring the same area in disaster surveillance. However, support services such as the supplementing of helium gas are required. Helicopters can hover as well, but require a greater amount of energy and have limited continuous operation times. Airplanes find it difficult to both hover as well as to adapt to the route according to the situation. In addition, similar to helicopters, their continuous operation times are limited. An airship requires a relatively large space for periodic topping-up of its helium gas, takeoff, and landing, and an airplane needs a long runway or special care for takeoff and landing. These support services are unnecessary for a helicopter.

IV. SURVEILLANCE ARCHITECTURE

A. Overview

In the proposed architecture, an EV–EH pair is the key component for the surveillance of disaster-affected areas. Each EV functions as the carrier of its partner EH during the round trip to the designated destination and surveillance, providing its roof area for accommodation, takeoff, and landing of the EH. It also may support automatic piloting for its partner EH. Each EV and EH are equipped with sensing and wireless communication devices. For conducting time-efficient and pervasive surveillance activities over a wide disaster-affected area, a number of EV–EH pairs may be used for simultaneous and parallel surveillance over said area. To start surveillance, each EV accompanied by its partner EH is driven to and parked at its target point in the disaster-affected area. During this phase, the EH may get and provide information useful for EV driving, e.g., existence of obstacles and traffic congestion on streets, to the EV driver.

A designated EV within the area is assigned the role of the data collection node (simply center EV, hereafter). The sensed data are delivered from each source EV or EH by means of wireless multi-hop communication relayed by a number of EVs or EHs on the way to the center EV, and then to the remote disaster recovery headquarter, using, for instance, a satellite communication link. Disaster-affected area surveillance by EVs on the ground and that by EHs in the air can work in a complementary, cooperative manner, thus significantly improving the efficiency and accuracy of surveillance.

B. Area division requirements

Area division is useful for coordinating and assigning surveillance activities among multiple EV–EH pairs, where the entire surveillance area is divided into multiple non-overlapping sub-areas filling the entire area and an EV–EH pair is assigned to each sub-area. Surveillance activities are independently and simultaneously performed in parallel within each sub-area. In general, the greater the number of EV–EH pairs, the less is the time required for one round of surveillance of the entire area; the required time can be reduced further, although at the cost of EV–EH pair resources.

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C. Wireless multi-hop data delivery

Upon reaching the target point in the assigned sub-area, each EV remains at this initial position during the following surveillance activities as the support station, while its partner EH flies over the entire assigned sub-area for surveillance and sends the gathered surveillance data to its partner EV, which works as the temporal data storage point. The EV then forwards the data to the neighbor EH flying over the adjacent sub-area, which is located on the designated path toward the center EV. The neighbor EH receives this data and forwards it to its partner EV, in addition to the data gathered by itself. This process is repeated and the data obtained by the source EH are eventually delivered to the center EV. In addition to EHs, EVs may gather and transmit surveillance data. Area division needs to be performed to ensure that an EH and its partner EV, and an EV and its upstream EH in the adjacent sub-area on the designated path toward the center EV are within the transmission range (Requirement 1). Each EV and EH may have multiple down-stream EHs and EVs, respectively. Simultaneous packet transmission to the same EH and EV may result in interference, and, thus, the use of non-overlapping channels is desirable for avoiding interference.

D. Line-of-sight transmission using flying EH

It is noteworthy that data packets can be transmitted between the EV and the EH in the proposed architecture, thereby avoiding EH–EH or EV–EV transmission. In the EH-EH, packet transmission could be unstable due to variations in the EH position or attitude in air even in the hovering state. In the EV-EV, line-of-sight may not be assured due to the obstacles on the ground, thus resulting in poor packet transmission performance. In contrast, it is easier to assure line-of-sight in the EH–EV packet transmission. Moreover, a directional antenna can be attached to the side of the EV, which can significantly extend the packet transmission range [19].

E. Flight time and range requirement

To minimize EH total weight, the weight of the battery is strictly limited. This means that the EH's battery capacity is also limited, allowing only relatively short continuous flight times and ranges. The EV's battery can be used for recharging the partner EH's spent battery, thus allowing the EH to engage in airborne surveillance repeatedly [15]. This functionality is termed as "on-EV charging." A carrier EV can be equipped with spare EH batteries. By substituting a spare EH battery for the landed EH's spent battery, the waiting time for on-EV charging can be shortened as mentioned in Section III.C. The spent battery from the EH is recharged on the EV for reuse. EH flight time must be set at least longer than the round trip time between the positions of its partner EV as the on-EV charging station and the farthest part within the sub-area (Requirement 2).

V. SURVEILLANCE SCHEME

A surveillance area is a square of size $L \times L$, which is uniformly divided into $n \times n$ square sub-areas, each of size $L/n \times L/n$, as shown in Figure 1. An EV–EH pair is

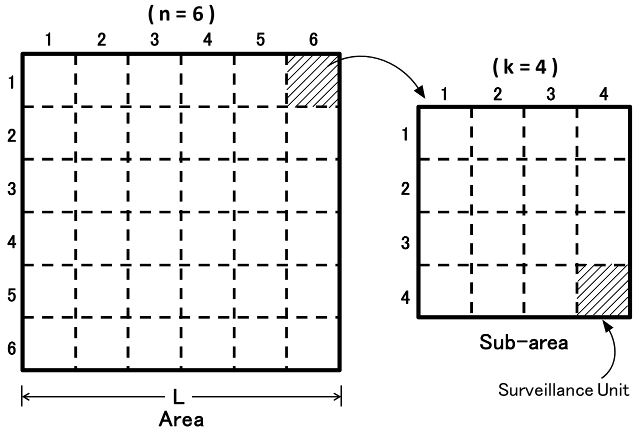

Figure 1. Example of area division in square area modeling.

assigned to each sub-area. Each EV is positioned in the center of the respective assigned sub-area. The center EV is positioned in the center sub-area. A sub-area is further divided into uniform squares, each of which, termed "a surveillance unit," is the field of vision, with the length of each side, d', closest to and no greater than the given value, d, to make uniform division. Each surveillance unit can be surveyed by an EH flying over the center line crossing the center of the surveillance unit without approaching the edges of the surveillance unit. Let $F_{\max}$ be the maximum flight distance divided by the side length of the surveillance unit (normalized flight distance) of an EH. Requirement 2 in Section IV.E can then be represented by

$$\begin{aligned} F_{\max} &\geq 2k & (k: even) \\ &\geq 2(k-1), & (k: odd) \end{aligned} \quad (1)$$

where $k = L/n/d$.

Because the EH needs to return to its partner EV before running out of battery for on-EV charging to continue further surveillance, the normalized flight distance, D, required for completing one-round surveillance of a sub-area is represented as the following function of k and $F_{\max}$:

$$D = f(k,\ F_{\max}). \quad (2)$$

The upper bound of D, D_{ub}, is then given by substituting $F_{\max}$ with its lower bound in (1)

$$\begin{aligned} D_{ub} &= f(k,\ 2k) & (k: even) \\ &= f(k,\ 2(k-1)). & (k: odd) \end{aligned} \quad (3)$$

In contrast, if there is no limit on the battery capacity, the EH can continue surveillance by taking an optimum route over the sub-area without returning to its partner EV. The lower bound of D, D_{lb}, is thus obviously given by

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$$D_{lb} = k^2 \qquad (k : even)$$
$$= k^2 + 2 . \qquad (k : odd) \tag{4}$$

The time required for completing one-round surveillance of a sub-area (one-round surveillance time), T is given as

$$T = D\tau , \tag{5}$$

where τ is time required to cross the side length of the surveillance unit in flight. It is noteworthy that the time of on-EV charging is not included in (5) based on the remark in Section IV.E. The surveillance time, T, should be designed to be no greater than its upper bound $T_{\max}$, which may be given as the design target parameter in surveillance system development, as shown below.

$$T \le T_{\max} . \tag{6}$$

Let β (MB/km^2) be surveillance data size per unit area. The total surveillance data size of the surveillance area is then βL^2. As described in IV. C, a designated path toward the center EV should be set for data transfer from each sub-area to the center area. Because surveillance data from each sub-area are merged at each relay EV and EH, the transmission load increases for the upstream EVs and EHs closer to the center EV. Four most-upstream EHs are adjacent to the center EV in the square area modeling considered in this section. Assuming that the set of designated paths for the area is designed to balance the transmission load among the links, and neglecting the transmission overhead, the maximum link load, B (Mbps), can be represented as

$$B = \frac{2\beta L^2}{T} \qquad (n : even)$$
$$= \frac{2\beta L^2 (n^2 - 1)}{Tn^2} . \qquad (n : odd) \tag{7}$$

An example of the designated path configuration is given in Figure 2.

The transmission range of a wireless link can be defined as the maximum distance over which the packet loss rate is no greater than the given threshold. In general, the transmission range becomes shorter as the effective bandwidth increases; thus, the transmission range is a function of B, represented by $R(B)$. The transmission distance can be the longest when the EV in the center of each sub-area transmits packets to the upstream EH at the far-end corner of the adjacent sub-area on the designated path to the center EV. For satisfying Requirement 1 in Section IV.C, the following relationship should be satisfied.

$$\frac{\sqrt{10}L}{2n} \le R(B) . \tag{8}$$

In contrast, the number of EV–EH pairs covering the surveillance area should be maintained as low as possible for cost saving.

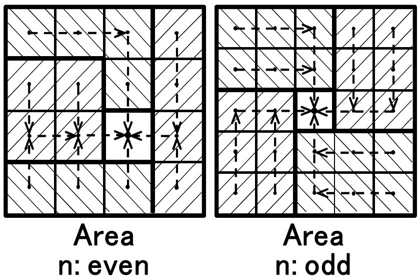

Figure 2. Example of designated path configuration to center EV.

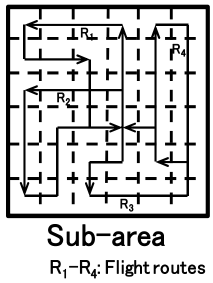

Figure 3. Example of flight path configuration.

An area division solution for the square area and sub-area models should thus obtain the minimum value of n for satisfying conditions (6) and (8), where B is substituted by (7).

VI. Numerical Examples

Investigation of the characteristics of the function in (2) is an interesting research issue, but is out of the scope of this study. Instead, the upper bounds of the normalized flight distance, D_{ub}, in (3) can be given numerically using the flight path configuration obtained by a heuristic approach (See Figure 3). The results, including the D_{lb} of (4), are shown in Figure 4. The ratio of D_{ub} to D_{lb} is also shown in Figure 4. It is expected that the ratio roughly converges to around 1.2.

The upper bounds of the one-round surveillance time are obtained by substituting D with D_{ub} in (5) and shown in Figure 5, where L and EH velocity are 50 km and 60 km/h, respectively. As expected, the one-round surveillance time decreases with an increase in the number of divisions or the field of vision. Similarly, the transmission range requirement given in (8) decreases with an increase in the number of divisions, as shown in Figure 5.

Assuming use of an adequate transmission system meeting required effective bandwidth and transmission range for each EH–EV or EV–EH link, link quality such as packet delivery ratio can be assured, while end-to-end path quality degrades as the number of divisions of sub-area increases. To improve end-to-end path quality, packet retransmission mechanism either in link or end-to-end may be required.

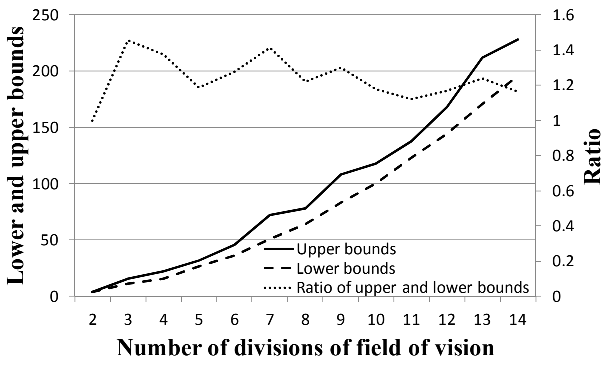

Figure 4. Lower and upper bounds of normalized flight distance, D and ratio of upper bounds to lower bounds.

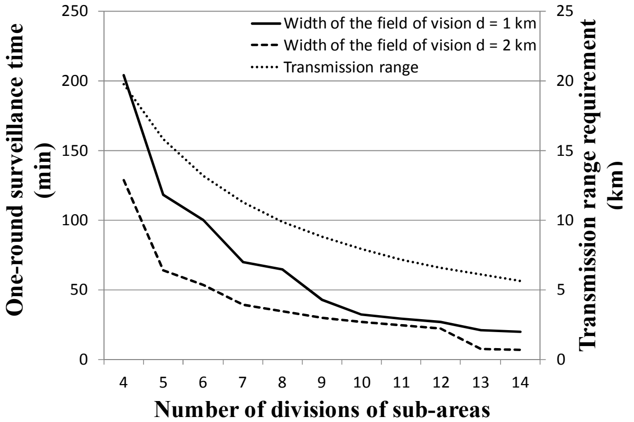

Figure 5. Upper bounds of one-round surveillance time and transmission range requirement with regard to number of divisions, n.

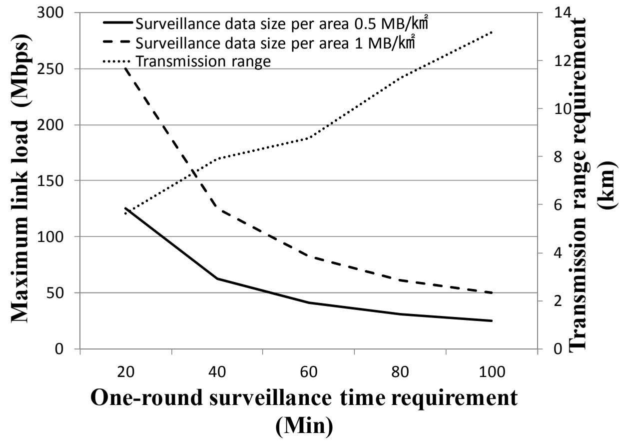

Figure 7. Maximum link load and transmission range requirement meeting given one-round surveillance time requirement.

The number of divisions, n, meeting the given one-round surveillance time requirements is obtained from (3), (5) and (6) and shown in Figure 6. The higher the one-round surveillance time requirement, the lower is the number of divisions of a sub-area. The corresponding maximum link load in (7) and transmission range requirements in (8) are shown in Figure 7. As the one-round surveillance time requirements rise, the surveillance data transmission frequency decreases, resulting in a decrease in the maximum link load. By contrast, the transmission range requirements increase owing to an increase in the sub-area size. Therefore, given the one-round surveillance time requirements, an adequate transmission device should be selected based on the requirements of decrease in the maximum link load and increase in the transmission range.

In summary, the numerical examples in Figure 6 show that wide area as large as 100 km square can be monitored pervasively in one hour or so, operating a few hundred EV–EH pairs. Transmission devices meeting the requirements as shown in the numerical examples in Figure 7 can be in the scope of the existing technologies.

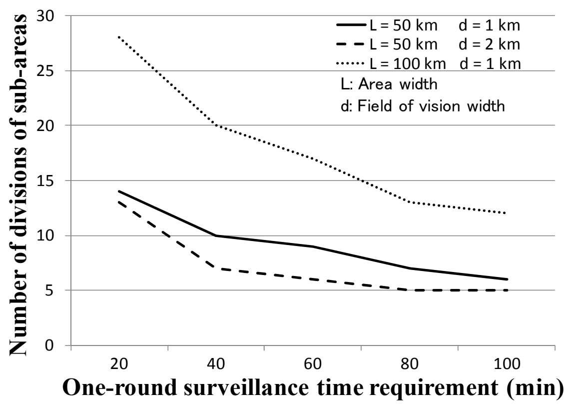

Figure 6. Number of divisions, n, meeting given one-round surveillance time requirement.

VII. CONCLUSION AND FUTURE WORK

A time-efficient and pervasive surveillance architecture based on the collaboration of multiple EHs was presented. A wide area is divided into a number of sub-areas. An EH and its partner EV, which supports automatic piloting and battery charging for the EH, are assigned to each divided sub-area. A wireless link is established between an EH and its partner EV, as well as between an EV and its immediate upstream EH for forming a wireless multi-hop path toward the data collection node in the area. Area division principles were used considering cost minimization as well as considering the requirements of allowable surveillance time, and transmission range and effective bandwidth of the wireless link. A simple model and approach for area division based on explicit flight route distances of an EH considering the battery-capacity-limited flying range were presented. Numerical examples showed the feasibility of the area division approach.

Further studies on this subject include the development of a general algorithm for obtaining the explicit flight route of EHs for not only simple square area models but also for geographical areas of any shape under flight distance limitations. Communications aspects, such as performance evaluation and improvement of wireless multi-hop communication path composed of multiple EH–EV and EV–EH links, are also included in the further study issues.

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