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Utility Based Scheduling for Multi-UAV Search System in Disaster Areas

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ABSTRACT Micro or small unmanned aerial vehicles (UAVs) is a promising solution for finding people who have disappeared because of getting lost in unexpected situation like disaster. It takes long time to analyze the acquired image data for the target recognition due to the limited computational resource of small UAVs. In addition, the data transfer time can increase in the disaster-hit areas due to the damage of communication infrastructures. However, the prior researches did not consider both processing time of the acquired data and data transfer time, despite the temporal requirement in the surveillance scenarios. Therefore, this paper proposes a scheduling method of multi-UAV search system that considers processing time of image data and data transfer time. We present the utility-based problem formulation that ensures the freshness of individual obtained piece of information while obtaining as many pieces of information as possible for a certain period. Simulation results verify that the proposed scheduling method ensures the freshness of individual obtained piece of information while delivering as many pieces of information as possible for a certain period by evaluating each information in terms of two metrics: i) elapsed time from start time and ii) elapsed time after acquired.

INDEX TERMS uav (unmanned aerial vehicle), target search, scheduling, edge computing

I. INTRODUCTION

The number of deaths and missing people due to natural disasters is still a serious problem in many countries. According to a report by Centre for Research on the Epidemiology of Disasters [1], the average number of deaths and missing people due to natural disasters occurred all over the world, such as earthquakes, hurricanes, forest fires, and floods, from 2006 to 2015 was approximately 70,000. In order to reduce the number, one of the solutions to reduce the number is to increase the number of rescue teams. The report by Japan Ministry of Defense after the great east Japan earthquake suggests that it is necessary to secure manpower through guidelines for the concentration of units in the immediate aftermath of a disaster. However, a huge budget is required to secure manpower and the risk of secondary damages in disaster occurrence areas is serious remaining issues to be solved [2]. Micro or small unmanned aerial vehicles (UAVs), also known as drones, are expected to be emerging solutions to solve the above problem in areas where humans and ground vehicles cannot easily step into like disaster-damaged areas. Technological advances in the recent years have led to the emergence of smaller and cheaper UAVs, which have some functions such as transporting relief supplies, collecting data by using equipped sensors and operating as adhoc wireless mesh network infrastructure in such isolated areas [3]–[5]. Collecting image data is especially important because it is applicable to many use cases such as search and rescue mission, fire detection and surveilance. Since there are time constraints in such situations, UAVs need to collect sensor data as soon as possible. In the great east Japan earthquake, as time passed, the number of deaths and missing people dramatically increased [6]. Surveillance using multiple UAVs has been receiving increasing attention for reasons such as increase in system reliability, robustness, and efficiency [7]–[11]. However, despite the temporal requirement in these surveillance systems, it is assumed that the user can obtain necessary information as soon as UAV acquires image data: both processing time of image data and data transfer time are not taken into consideration. In the practical situation, it takes long time to analyze images for target recognition due to the limited computational resource of small UAVs. In addition, the data transfer time can increase in the disaster-hit areas due to the damage of communication infrastructures.

Therefore, this paper proposes a scheduling method of multi-UAV search system that considers processing time of image data and data transfer time. We present the problem formulation of the proposed scheduling method that maximizes the user' s utility, which is calculated from the efficiency of obtaining results from analyzed data and the interval of obtaining the results. We show the results of performance evaluation to verify that the proposed method ensures the freshness of individual obtained piece of information while delivering as many pieces of information as possible for a certain period.

The remainder of this paper is organized as follows. Section II discusses the related work. Section III presents the system overview and proposed scheduling method. Section IV then provides the performance evaluation of the proposed method through a simulation, followed by the extension to two-dimensional model in Section V. Finally, Section VI concludes this paper.

II. RELATED WORK

This section discusses the prior works related to this paper. First we will discuss UAV Applications in disaster areas. Among the application scenarios that will be introduced in Section II-A, data collection using equipped sensors is carried out in our system. Next the prior researches on Multi-UAV cooperation for area coverage is discussed since it is also assumed in our search system as mentioned in Section I. Finally, we also discuss prior works on inter UAV cooperation for computing and computing on UAVs with edge computing. In our system, it is assumed that the collected data is processed locally onboard UAVs with edge computing but inter UAV cooperation for computing is not considered since the overhead of transmission between UAVs is large and is out of the scope of this paper.

A. UAV APPLICATIONS IN DISASTER AREAS

Transporting relief supplies by UAVs is very important since there is a possibility that humans and ground vehicles cannot easily step into the disaster areas. Bamburry mentioned the ability of a UAV to deliver medical products to remote and hard-to-reach areas [12]. For example, in the devastating 2010 earthquake in Haiti, a UAV delivery system was used to deliver medicine to camps set up after the disaster [13].

UAVs can also collect data by using equipped sensors. In [14], Each UAV is provided with a mobile optical sensors and image transmission modules developed by the Wada et al. The optical sensor which is a combination of a IR sensor and a visible-light sensor enables data collection even at night or against smoke in the disaster areas. After the launch, a UAV executes auto flight along the way points by recognizing its positions and obtains the necessary video/image information. The UAV transmits it to the server and shares it with users via the Internet.

UAVs also often operate as adhoc wireless mesh network infrastructure, which is called Flying Ad Hoc Networks (FANET) [15]. In 2016, Sánchez et al. aim to provide connectivity for rescuers and disaster victims using UAVs [16]. They propose a Jaccard-based movement rules to define the UAVs best positions for providing the best communication service to the victims in a urban disaster scenario. Finally they compare among several local search computational intelligence algorithms implemented such as simulated annealing, hill climbing, and random walk for deciding the best tactical UAV movements.

B. MULTI-UAV COOPERATION FOR AREA COVERAGE

Maza et al. provided a pioneer work in cooperatively searching a given area to detect objects of interest by UAVs [8]. First they determine relative capabilities of each UAV, based on factors like flight speed, altitude required for the mission, sensitivity to wind conditions and sensing width. Then, they divide the whole area by divide-and-conquer, taking into account the UAV' s relative capabilities and initial locations. Finally, they set the waypoints of each UAV so that the number of turns needed along a zigzag pattern is minimized.

Zhao et al. in 2016 tackled the challenging problem of not only searching the target area for a lost target but also tracking the target [10]. In the tracking stage, each UAV keeps desired distance with the target, coordinating the angular separation between neighboring UAVs to the same angle. if there is a shelter between UAV and target, the target state is predicted by the target model with the former target information. In the searching stage, multi-UAVs divide the search region equally which is determined by the target lost duration time and speed and then search for the target by the method of shrinking annulus. The switch tactics between the tracking stage and the searching stage was also proposed.

In 2017, Hayat et al. proposed a multi-objective optimization algorithm to search and plan paths for UAVs [17]. UAVs search for the target cooperatively and soon after some UAV detects the target, the other UAVs takes positions for relay chain formation between the UAV and a base station. The algorithm aims to minimize the mission completion time, which includes the time to find the target and the time to setup a communication path. Finally they compare among three strategies that perform search by UAVs in a similar manner but have a different path planning in terms of the mission completion time.

C. MULTI-UAV COOPERATION FOR COMPUTING

UAV Applications in disaster areas require UAVs to deal with intensive computation tasks such as image/video processing, pattern recognition and feature extraction. Computation offloading is very important since computational power of a single UAV is limited.

1) inter UAV cooperation

Ouahouah et al. in 2017 proposed the use of offloading mechanism among UAVs equipped with IoT devices [18].

Each IoT task is partitioned into a set of sub-tasks that can be executed simultaneously among a cluster of UAVs. The sub-tasks is assigned to UAVs based on their power supply, resources in terms of memory and CPU computation, and their on-board IoT devices. Two solutions were proposed for computation offloading:Energy aware optimal task offloading and Delay aware optimal task offloading. The former maximizes the UAVs lifetime by electing the UAVs with higher power supply. The latter reduces the response time by favoring the selection of UAVs with more resource capacities.

In 2018, Valentino et al. proposed an opportunistic and adaptive computational offloading scheme between UAV clusters [19]. A cluster head will broadcast a 'hello' message indicating their presence and available resources and then a local cluster send an offloading request to a desired cluster head. a local cluster decides if it is better to do the task alone or to offload, estimating response time for doing the computational offloading and processing the given task through computing power, size of task, bandwidth, and data rate of wireless network.

2) Edge computing

Edge computing has been proposed as an effective mean of supplementing computational resources for UAVs [20], [21].

Motlagh et al. in 2017 demonstrated how UAVs can be used for crowd surveillance based on face recognition. Due to the computational overhead required by such a use case and given the limited power supply of UAVs, they performed the offloading of video data processing to a mobile edge computing node. The obtained results showed clearly the benefits of computation offloading compared to the local processing of video data onboard UAVs in saving energy and quickly detecting and recognizing suspicious persons in a crowd.

Messous et al. in 2017 tackled a computation offloading problem with three different devices: UAV, base station and edge server, which carry out the heavy computation tasks. They prove the existence of a Nash Equilibrium and design an offloading algorithm that converges to the optimal point. Their cost function was defined as a combination of two performance metrics: energy and delay. They finally achieved better value of the utility using the the offloading algorithm, compared to computing on: edge server, base station and drone respectively.

III. PROPOSED METHOD

A. SYSTEM OVERVIEW

1) System model

Figure 1 depicts the system model we assume in this paper. The system consists of a user device (UD), multiple UAVs, and an edge server (ES), the roles of which are described as below. The UD is the central operating entity in the system and operates all the UAVs and the ES; the UD determines flying routes and timings of UAVs and assigns workloads of computing sensor data to UAVs and the ES. The UD also works to forward sensor data received from UAVs to the ES and to obtain computational results from both UAVs and the ES.

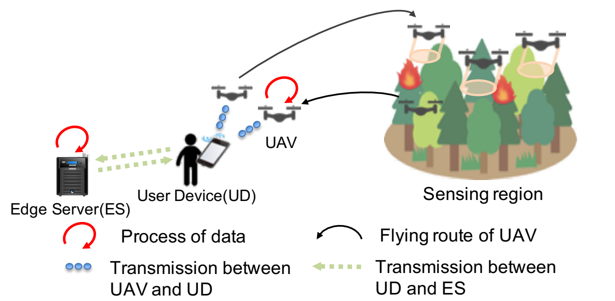


FIGURE 1: System illustration

Each UAV is operated by the UD and performs the following actions autonomously in the distributed manner. (I) Flying between the initial position, at which the UAV can communicate directly with the UD, and the sensing region assigned to the UAV (II) Acquiring image data (still or moving images) of the sensing region assigned to the UAV. (III) Staying at the initial position and performing the following actions in parallel: (a) analyzing a part of collected image data with the computational power of the UAV and (b) delegating the analysis of the rest of the data to the ES. (IV) Reporting results obtained from the analysis of image data to the UD soon after it has been completed. Note that we assume that UAVs cannot perform any analysis while flying; computational resources of UAVs are fully used for flight control and image acquiring during the flight.Each UAV repeats all the actions (I) to (IV). We call one action (I) to (IV) of some UAV one round.

The ES is placed closely to the UD and works to perform the analysis of a part of image data received from UAVs. Like UAVs do, soon after the ES has completed the analysis, it reports the results to the UD.

2) System flow

In the system we assume in this paper, the schedules of flying, acquiring, and analyzing of UAVs are determined through the following steps:

- (1) Check if there is one or more UAVs the schedules of which have not been determined yet.
- (2) Pick one of the unscheduled UAVs and label it as UAV $i (i = 1, 2, 3 \cdots)$, if step (1) is yes.
- (3) Refer to the information about the schedules of UAVs $i-1, i-2, i-3, \cdots$, which were scheduled before UAV i.
- (4) Determine the schedule of UAV i by a scheduling method, which will be described later.
- (5a) Increment i to $i+1$. Go back to step (1).
- (5b) UAV i starts its operation based on the determined schedule and will be added to the list of unscheduled UAVs after completing all the actions (I) to (IV) mentioned in Section III-A1.

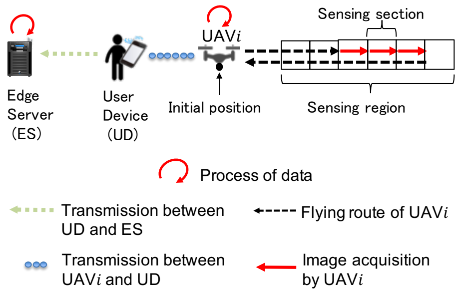


FIGURE 2: System model for problem formulation

Note that (5a) and (5b) are executed in parallel. At step (4), the scheduling method requires some time for calculating the schedule of UAV i. The calculating time depends on the complexity of the scheduling method. Therefore, the complexity of the scheduling method should not be complicated. However, from the second round of the scheduling for a UAV, the calculation can be done in advance while the UAV is performing step (5b) because all the previous schedules before the UAV have been determined already and the information of all the previous schedules are available. When the ES receives a computational task from a UAV via the UD, the ES puts it to the waiting queue. The ES processes those computational tasks in the first-in first-out (FIFO) manner and reports the result to the UD immediately after finishing each computational task.

B. PROPOSED SCHEDULING METHOD

We assume the system model shown in Figure 2, in which sensing sections are placed on the one-dimensional line and their sizes are identical. Sensing sections are assigned to UAVs from the one closest to the initial position and only an image is acquired at each sensing section. These assumptions allow us to simply deal with the sensing range of each UAV as the number of images acquired by them. We also assume that, if the computing resource of ES or the communication channel of UD is still used by previously scheduled UAVs (UAVs $1, 2, \cdots i-1$), UAV i has to wait in the first-in first-out (FIFO) manner until their operations are completed. This also means that the operation of UAV i does not affect the operations of the previous UAVs (UAVs $1, 2, \cdots i-1$).

1) Utility

This section presents the mathematical formula of the utility function. The utility function of UAV i in the proposed method, U^i, is given as:

$$U^i = \frac{\eta^i}{\Delta t^i}, \tag{1}$$

where η^i means the efficiency of obtaining results from analyzed data and Δt^i is the interval of obtaining the results. They are called acquisition efficiency and acquisition interval, respectively, and defined as:

TABLE 1: Definition of notation

	Description
N^i	No. of images acquired by UAV i
N_u^i	No. of images processed by UAV i in N^i
N_e^i	No. of images delegated from UAV i to ES
T_{ng}	Flying time per sensing section
T_g	Image acquisition time per sensing section
T_f	Flying time from initial position to left-end of sensing sections
$T_{u,d}^i(N^i, N_u^i)$	Transmission waiting time from UAV i to UD
$T_{d,e}^i(N^i, N_u^i)$	Transmission waiting time of UAV i's data from UD to ES
$T_e^i(N^i, N_u^i)$	Processing waiting time at ES
$\mu_{u,d}$	Transmission speed from UAV i to UD in no. of images per unit time
$\mu_{d,e}$	Transmission speed from UD to ES in no. of images per unit time
P_u^i	Processing speed at UAV i in no. of images per unit time
P_e	Processing speed at ES in no. of images per unit time

$$\eta^i = \frac{N^i}{t_{fin}^i - t_{start}^i} \tag{2}$$

$$\Delta t^i = t_{fin}^i - t_{fin}^{i-1} \quad (t_{fin}^0 = 0, t_{fin}^i \geq t_{fin}^{i-1}), \tag{3}$$

where N^i means the number of images acquired by UAV i, t_{start}^i is the flight start time of UAV i, and t_{fin}^i is the time when processing N^i images is finished. The utility function in defined by (1) suggests that, as the acquisition efficiency and interval become higher and shorter, the system works better for users. The reason why it is reasonable is because, in surveillance scenarios, users would expect to obtain as many pieces of information as possible during a certain period, while more updated information would be more valuable for them.

2) Problem formulation

This section discusses the problem formulation of the proposed scheduling method. Table 1 lists the definition of the notation we use. In this table, N^i, N_u^i, and N_e^i are variable. Using the notation, the problem formulation is described as below:

$$\underset{N^i, N_u^i}{arg\ max} \quad U_i = \frac{\eta^i}{\Delta t^i} = \frac{N^i/(t_{fin}^i(N^i, N_u^i) - t_{start}^i)}{t_{fin}^i(N^i, N_u^i) - t_{fin}^{i-1}} \tag{4}$$

$$s.t. \quad N_{MIN}^i \leq N^i, \tag{5}$$

where N_{MIN}^i means that UAV i has to acquire at least N_{MIN}^i images so as not to complete its actions earlier than the previous UAV, UAV $i-1$: $t_{fin}^i \geq t_{fin}^{i-1}$. This formulation suggests that N^i and N_u^i must be determined so that the utility function, U^i, is maximized.

t^i_{fin} in (4) is represented as:

$$t^i_{fin}(N^i, N^i_u) = t^i_{start} + 2(T_f + \sum_{j=1}^{i-1} N^j T_{ng}) + N^i(T_g + T_{ng}) + \max(\frac{N^i_u}{P^i_u}, T^i_{u,d}(N^i, N^i_u) + \frac{N^i_e}{\mu_{u,d}} + T^i_{d,e}(N^i, N^i_u) + \frac{N^i_e}{\mu_{d,e}} + T^i_e(N^i, N^i_u) + \frac{N^i_e}{P_e}). \quad (6)$$

Eliminating N^i_e from (6) using $N^i = N^i_u + N^i_e$, $t^i_{fin}(N^i, N^i_u)$ becomes a function of two variables, N^i and N^i_u. According to (6), $t^i_{fin} - t^i_{start}$ is equal to the sum of flight time, transmission time, and processing time of UAV i. The second and third terms in the right side of (6) represent the flight time outside the sensing range of UAV i and the sum of the image acquisition time and the flight time within the sensing range assigned to UAV i, respectively. The max function of the fourth term in the right side of (6) is the processing time of N^i images, which is equal to the longer one of the image processing time at the UAV i or the total consumed time for image transmission from UAV i to the ES and the image processing at the ES. $T^i_{u,d}(N^i, N^i_u)$, $T^i_{d,e}(N^i, N^i_u)$, and $T^i_e(N^i, N^i_u)$ in the right side of (6) are waiting times for UAV i. As we mentioned before, if previous UAVs (UAV1,UAV2,$\cdots$, UAV$i-1$) are still using the communication channel of the UD or the computational resource of the ES, UAV i has to wait for a certain waiting time until all the transmission and processing tasks have been completed. That is, t^{i-1}_{fin}, which is the time when processing N^{i-1} images acquired by UAV $i-1$ is finished, is not affected by the operation of UAV i and can be dealt as a constant value in the scheduling of UAV i. Note that we assumed, since the size of output data obtained after processing at UAVs and the ES is quite small, transmission time of those output data is negligible.

N^i_{MIN} in (5) is the specific value of N^i that satisfies the following condition:

$$\underset{N^i, N^i_u}{arg\,min} \quad t^i_{fin}(N^i, N^i_u) \quad (7)$$

$$s.t. \quad t^i_{fin}(N^i, N^i_u) \geq t^{i-1}_{fin}(N^i_u \in \mathbb{N} \mid 0 \leq N^i_u \leq N^i). \quad (8)$$

Here, suppose that N^i_u is determined so as to minimize $t^i_{fin}(N^i, N^i_u)$ for a given N^i. For such N^i_u, N^i_{MIN} is the minimum integer among possible values of N^i that satisfy Formula (8). By setting N^i_{MIN} so, as long as N^i_u is chosen so as to satisfy $0 \leq N^i_u \leq N^i$, the optimal N^i in (4) can be determined among the possible values of N^i that satisfy $U^i(=\frac{\eta^i}{\Delta t^i}) > 0$.

C. FEATURE OF PROPOSED SCHEDULING METHOD

Our proposed scheduling method is service-centric; since it has service-centric features as listed below.

- Robustness for the increase or decrease of numbers of UAVs: UAVは途中で追加されたり，故障で台数が減少する可能性がある．提案方式は一台ずつ逐次的に制御するため，そういったケースに対応可能である．
- Applicability for the Heterogeneity of UAVs: 各UAVの飛行速度や計算能力には個体差がある．提案方式ではそういった個体差を考慮してスケジューリングすることが可能である．
- applicability for the various kinds of processing capacities of UAVs and ES: 各UAVとESの計算能力はマシーン性能に大きく依存する．提案方式では各UAVやESの計算能力を最適に利用することが可能である．
- Feasibility for various types of geographical areas: earthquakes, hurricanes, forest fires, and floodsなど様々な災害に応じてgeographical areaも多種多様である．提案方式では，様々なgeographical areaにおいて，用いることが出来る．

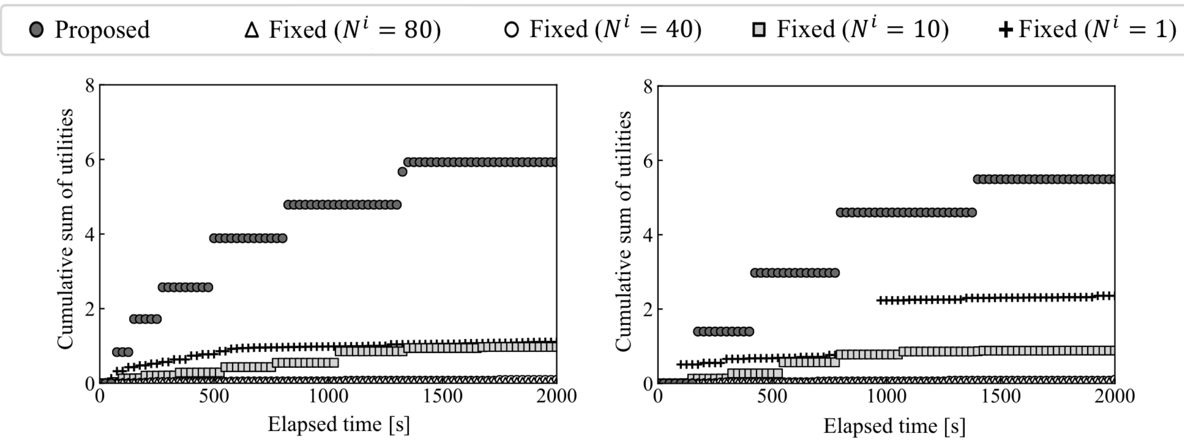
IV. BASIC PERFORMANCE EVALUATION

A. SIMULATION SCENARIO

A basic simulation was performed to validate the proposed scheduling method. We considered a surveillance scenario in which a rescue team uses the multi-UAV system illustrated in Figure 1 to find missing people in an area where humans and ground vehicles cannot easily step into. Although our scheduling method should be applicable for realistic scenarios, we assume a simple model illustrated in Figure 2, in which sensing sections are placed on the one-dimensional line and their sizes are identical, to present the problem formulation. Our simulation adopted the proposed scheduling method described in Section III-B and performed every step of the system flow described in Section III-A2. We compared the proposed method with one of the existing methods: fixed method, which simply assigns a fixed number of sensing sections to each UAV uniformly [10]. 固定方式ではN^iの内，UAVで処理する処理画像枚数N^i_u ($0 \leq N^i_u \leq N^i$)を決定する際は，N^iの画像処理が終了する時刻t^i_{fin}が最短となるように定めるものとする．提案方式と固定方式ともに，UAV iはN^i枚の画像処理が終了すると即座に次の飛行を開始する． Our basic evaluation adopts the following evaluation metric: Cumulative sum of utilities, defined by (1), against elapsed time. ユーザはUAVの処理結果を取得するごとに効用を受け取ることができるものとし，その累積和を考える．

B. SIMULATION PARAMETERS

The parameters used in our simulation are listed in Table 2. Considering the realistic specification of a recently commercialized UAV [22], we set the flying speed of UAVs to 15 m/s. The size of images was set to 100 kbytes, which corresponds to the one in the dataset called PASCAL VOC 2007 used in [23]. The consumed times for processing one image at UAVs and the ES are set corresponding to the consumed time for object recognition using GPU and CPU reported in [23], respectively. またUAVの個体差を考慮するために，各UAVの速度と単位時間あたりの画像処



(a) Elapsed time vs. Cumulative sum of utilities (D=200)

(b) Elapsed time vs. Cumulative sum of utilities (D=600)

FIGURE 3: Cumulative sum of utilities

理枚数はそれぞれ平均値μの10%を標準偏差σとする正規分布から$\mu\pm2\sigma$の範囲でランダムに設定した． The transmission rates of communication channel from UAVs to the UD and from the UD to the ES are set 100 Mbps, which is similar to the effective throughput of IEEE802.11n [25]. The proposed scheduling method finds out the local optimal solution, N_l^i, as we mentioned the datail in APPENDIX A. In our simulation, the range of local searching in the proposed scheduling method was set enough wide so that it can ensure that the local optimal solution equals to the true optimal solution. In addition, we assumed that the consumed time for finding out the local optimal solution is negligible; since the complexity of the scheduling algorithm is quite simple, the calculation can be finished in advance while the UAV is flying in the previous round.

C. RESULTS

図3は，提案方式と$N^i = 1, 5, 10, 50$での固定方式における，捜索開始時刻からの経過時間に対するユーザが取得した効用の累積和を表す．図3の(a)はDの値が200で，(b)では600である．いずれも時間の経過とともに単調増加しているが，DやMの値によって固定方式は優劣が変化する一方で，提案方式は常に値が最大となっている．よってユーザが得られる効用の累積和の観点において固定方式よりも提案方式の方が優れていると言える．

V. QOS EVALUATION

A. EXTENSION TO TWO-DIMENSIONAL MODEL

In this section, we mention that the proposed scheduling method described in Section III-B can be applied not only to the one-dimensional model in Figure 2 but also directly to the two-dimensional model. There are two assumptions in which the proposed scheduling method can be extended to the two-dimensional model shown in Figure 4 :

(1) Assuming fan-shaped sensing region, split the region so that each sensing section range is constant

(2) Each UAV executes sensing on the zigzag in order from the area closest to the center like [8]

TABLE 2: Simulation parameters

Parameters	value
No. of UAVs (U)	5
Average flying speed of UAVs	15 m/s
Distance between initial position and left-end of sensing block (D)	200,600m
Size of each sensing section	5 m
Consumed time for acquiring one image	2 s
Transmission rate of communication channel	100 Mbps
Size of image	100 kbytes
Average processing speed at UAV i in no. of images per unit time ($\overline{P_u}$)	$\frac{1}{1.83}$
Processing speed at ES in no. of images per unit time (P_e)	$\frac{1}{0.198}$

As shown in Figure 4, assuming that the vertical width of each partition is d and the central angle of the sensing region is θ [rad], the distance between each section when UAV moves in the direction opposite to the center of the region is d and the distance between each section when moving on the circumference is $\frac{1}{2}d\theta$. Therefore, when $\theta = 2$ [rad], all the distance between each section are equal as in Figure 2 and the proposed scheduling method described in Section III-B can be directly applicable to the Figure 4.

B. EVALUATION METRIC

In our QoS evaluation, we used the following three evaluation metrics.

・Elapsed time

評価指標の1つ目は探索エリアの各地点に対する2種類の経過時間である． The first one is ‘elapsed time from start time’ for each image, which is the elapsed time since the first UAV starts flying until the result about each image is

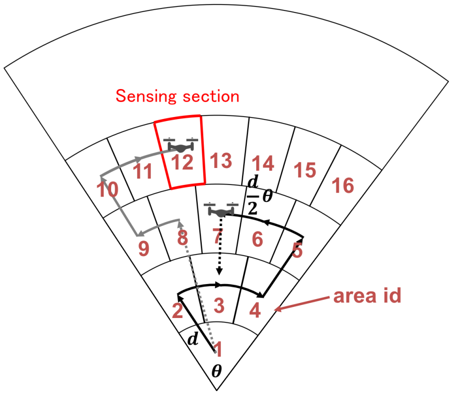


FIGURE 4: Sensing region of two-dimensional model

obtained by the UD. This metric is important for the rescue team because they need to know the information about each sensing section as soon as possible to know whether missing people are there or not. The second one is ‘elapsed time after acquired’ for each image, which is the elapsed time since an image is acquired at the corresponding sensing section until the result about the image is obtained by the UD. This metric is also valuable for the rescue team because it indicates the freshness of the information about each sensing section; the less updated information, the less reliable for them in searching missing people.

・Numbers of images whose elapsed time after acquired is a predetermined value or less at a certain time

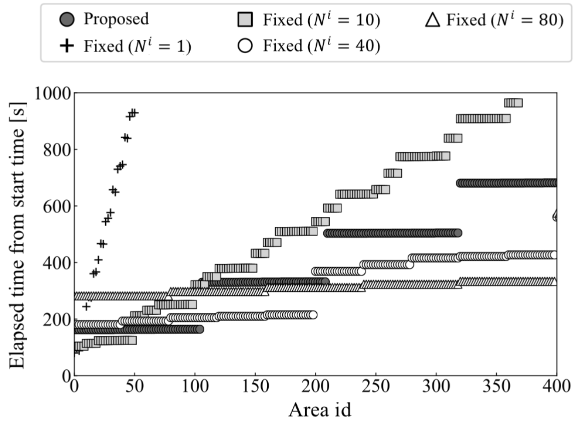
評価指標の2つ目は特定の時刻における取得時刻からの経過時間が一定以下の画像数である．画像処理が終了した画像数は探索が終了したエリア範囲を表すのでできる限り多いことが重要であるが，取得結果を受けて行方不明者を捜索する上では一定の鮮度を保っている，つまり取得時刻からの経過時間が一定値以下であることが重要である．そこでESの計算能力，UAVの初期位置と調査エリアの左端間の距離D，UAV台数Mを変数とし変化させた際に，提案方式と固定方式でその総数がどのように変化するかを考える．

・Cumulative sum of values

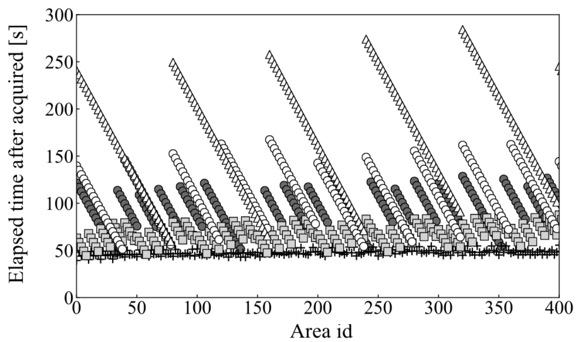
評価指標の3つ目は各時刻における価値の累積和である．ここで価値V_jは，ユーザが得る取得結果jに対応する画像が撮影されてからユーザが取得結果を得るまでの経過時間をtとして，以下のように表される [24]．

$$V_j = 2^{-\frac{t}{T_{half}}} \tag{9}$$

T_{half}は半減期を表す定数である．式(9)は，取得結果jの価値が画像が撮影された時刻に1を取り時間経過とともに指数減衰することを表す．半減期は救助隊が取得結果を受けて出動するまでの時間に応じて適切に設定する．ユーザは取得結果jを受け取るごとに価値V_jを受け取ることができるものとし，その累積和を考える．



(a) Area id vs. Elapsed time from start time



(b) Area id vs. Elapsed time after acquired

FIGURE 5: Two types of elapsed times

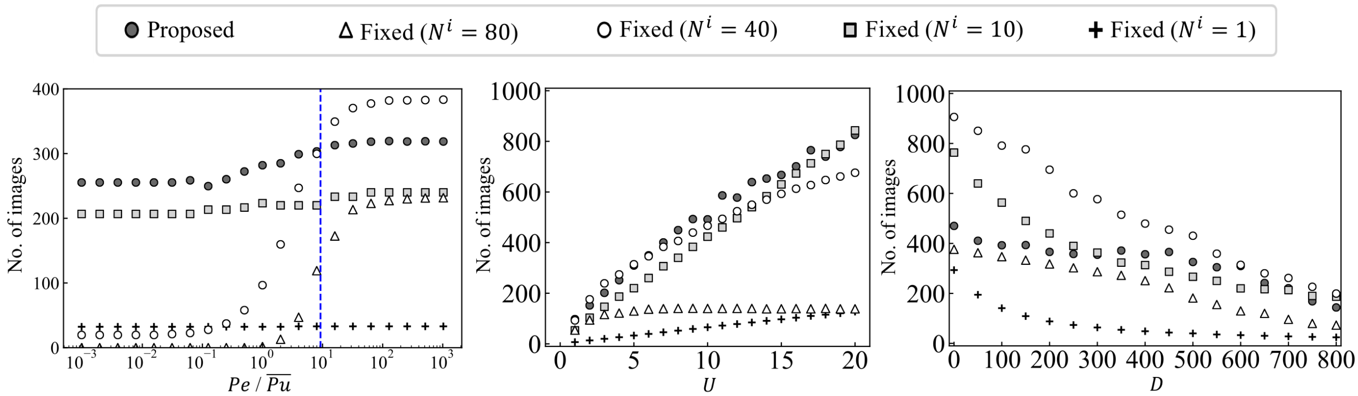
C. RESULT

We examined the fixed method with $N^i = 1, 10, 40$, and 80. In (a), for longer distance of sensing sections, the elapsed time from start time monotonically increases in all the methods. However, in the fixed method, as N^i was set larger, the elapsed time became shorter. The proposed method performed similarly to the fixed method with $N^i = 8$.

On the other hand, in Fig.(b), the elapsed time after acquired decreases with some regular pattern in all the methods. However, in the fixed method, as N^i was set smaller, the elapsed time became shorter. The proposed method worked between the fixed method with $N^i = 8$ and $N^i = 40$.

From the overall observation shown above, In the fixed method, $N^i = 40$ was most reasonable; its elapsed time from start time was the second best, while its elapsed time after acquired was much shorter than that of $N^i = 80$. The proposed method works similarly to $N^i = 8$, which suggests that it enables us to automatically achieve the most reasonable N^i.

次に各時刻における価値の累積和について考える．図7は提案方式と$N^i = 1, 5, 10, 50$での固定方式における，捜索開始時刻からの経過時間に対する価値の累積和を表す．図7の(a)(b)(c)の順に式(9)の半減期T_{half}の値が60，120，300 [s]となっている．(D, M)の値は，(200,5)と(400,15)でグラフの特徴に大差がなかったた

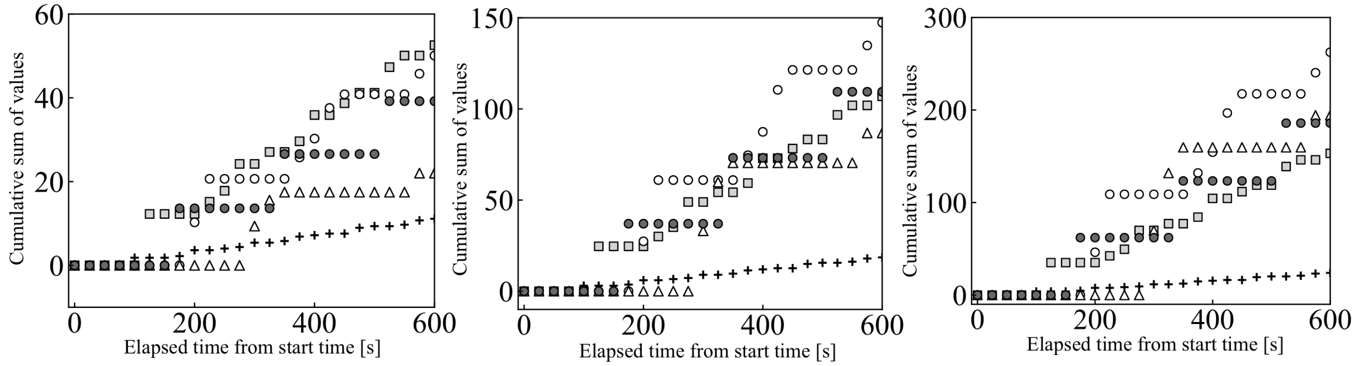


(a) Processing speed at ES vs. No. of images

(b) No. of UAVs vs. No. of images

(c) Distance between initial position and left-end of sensing block vs. No. of images

FIGURE 6: Numbers of images whose elapsed time after acquired is 120 [s] or less at 600 [s]



(a) Elapsed time from start time vs. Cumulative sum of values (T_{half} = 30 [s])

(b) Elapsed time from start time vs. Cumulative sum of values (T_{half} = 60 [s])

(c) Elapsed time from start time vs. Cumulative sum of values (T_{half} = 120 [s])

FIGURE 7: Cumulative sum of values

め，ここでは(200, 5)のみを採用した．いずれも時間の経過とともに単調増加しているが，半減期の値が大きくなるにつれて全ての方式で価値の累積和の値が大きくなっていることが分かる．また固定方式は半減期の値が120, 300 [s]の時は$N^i = 50$が最も価値の累積和の値が大きいが，60 [s]の時は$N^i = 50$は$N^i = 10, 5$と比べて価値の累積和の値が小さいように，半減期の値によって優劣が変化する．しかし提案方式は常に価値の累積和の値が大きいため，半減期の違いによる影響が小さい．よって各時刻におけるユーザが得た取得結果の価値の累積和の観点においてあらかじめ適切なN^iを定める必要がある固定方式よりも自動的に適切なN^iを決定できる提案方式の方が優れていると言える．

次に特定の時刻における取得時刻からの経過時間が一定以下の画像数について考える．図6はいずれも縦軸が2000 [s]時点において取得時刻からの経過時間が300 [s]以下の画像数を表しており，横軸については以下の通り．

図6(a):ESの計算能力．グラフでは$\frac{P_e}{P_u}$の値を10^{-3}から10^3の範囲でプロット．

図6(b):UAV台数Mを1から20の範囲でプロット．

図6(b):UAVの初期位置と調査エリアの左端間の距離Dを0から500の範囲でプロット．

図6(a)上の破線はP_eが表2に記した値の際の$\frac{P_e}{P_u}$を表す．また各値は三回の飛行の平均値である．グラフの左側はESの計算能力がUAVの計算能力と比べて十分に低い，つまりESが存在せずUAVでのみ計算処理を行う場合に対応し，グラフの右側はESの計算能力がUAVの計算能力と比べて十分に高い，つまりUAVで計算処理を行うことが出来ず全てESで計算処理を行う場合に対応する．

図6(a)より提案方式は$N^i = 50$の固定方式にのみ$\frac{P_e}{P_u}$が2.0×10^{-1}から10^3の範囲で劣っているが，10^{-3}から10^{-1}の範囲では提案方式が最も優れており，ESの計算能力によらず安定して値が大きいことが確認できる．同様に図6(b)(c)においても提案方式は固定方式と比較するとMやDの値による変化が小さく，平均して高い値を取っている．したがって図6(a)と(b)はいずれも単調増加し，図6(c)は単調減少しているが，自動的に適切なN^iを決定できる提案方式の方がパラメー

タの変化に対して強く，常に適切なN^iを定める必要がある固定方式より優れていると言える．

VI. CONCLUSION

This paper proposed a scheduling method of multi-UAV search system that considers processing time of the acquired image data and data transfer time in areas where humans and ground vehicles cannot easily step into like disaster-damaged areas. In this paper, we first showed the system model, which consists of a user device, multiple UAVs, and an edge server, and mentioned the sytem flow. We then presented the problem formulation of the proposed scheduling method that maximizes the user' s utility, which is calculated from the efficiency of obtaining results from analyzed data and the interval of obtaining the results, by using the one-dimensional model where sensing sections are placed on the one-dimensional line and their sizes are identical. A simulation was performed to verify that the proposed method works well to ensure the freshness of individual obtained piece of information while delivering as many pieces of information as possible for a certain period. The results indicated that the proposed method works better than the conventional fixed methods, in terms of two metrics: i) elapsed time from start time and ii) elapsed time after acquired for each image. For a more practical evaluation, in our future work, we will include prototype implementation and experiment.

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APPENDIX A OPTIMAL SOLUTION

This section discusses a solution of the problem formulation described in section III-B, which is used in our scheduling method. It takes long time to solve (4) and (5) due to their computational complexities, the calculation for scheduling could be non-negligible overhead in the system; UAVs have to wait to start flying until their schedules have been determined. Therefore, to simplify the calculation of (4) and (5), our scheduling method first supposes that all the waiting times for UAV i are equal to zero and obtains an approximated solution, N^i_{th}. Then, by searching locally around N^i_{th}, our scheduling method considers all the waiting times in (4) and (5) and finds out the local optimal solution, N^i_l. The following part explains the way of finding out N^i_{th}. First, we set all the waiting times to zero. Then, we replace the second and fourth terms in (6) with $2F$ and M, respectively. Then, by substituting t^i_{fin} in (6) to (1), we obtain $\frac{\eta^i}{\Delta t^i}$ as below:

$$\frac{\eta^i}{\Delta t^i} = \frac{N^i}{N^i(T_g+T_{ng})+2F+M} \times \frac{1}{N^i(T_g+T_{ng})+2F+M+t^i_{start}-t^{i-1}_{fin}} \tag{10}$$

where, by regarding N^i as a constant, only M is a variable and the value of $\frac{\eta^i}{\Delta t^i}$ varies dependently on the values of N^i_u and N^i_e. Since $\frac{\eta^i}{\Delta t^i}$ is always positive, M takes the minimum when $\frac{\eta^i}{\Delta t^i}$ takes the maximum. Although N^i, N^i_u, and N^i_e are integers, here we deal with them as real numbers.

Considering $N^i = N^i_u + N^i_e$, on the assumption that $\frac{N^i_u}{P^i_u}$ equals to $\frac{N^i_e}{\mu_{u,d}} + \frac{N^i_e}{\mu_{d,e}} + \frac{N^i_e}{P_e}$, we can obtain the value of N^i_u and N^i_e that satisfy $0 \le N^i_u$ and $N^i_e \le N^i$ as follows:

$$N^i_u = \frac{P^i_u(\mu_{d,e}P_e+\mu_{u,d}P_e+\mu_{u,d}\mu_{d,e})}{\mu_{u,d}\mu_{d,e}P_e+P^i_u(\mu_{d,e}P_e+\mu_{u,d}P_e+\mu_{u,d}\mu_{d,e})}N^i \tag{11}$$

$$N^i_e = \frac{\mu_{u,d}\mu_{d,e}P_e}{\mu_{u,d}\mu_{d,e}P_e+P^i_u(\mu_{d,e}P_e+\mu_{u,d}P_e+\mu_{u,d}\mu_{d,e})}N^i \tag{12}$$

When M takes the minimum value, $\frac{N^i_u}{P^i_u}$ is theoretically equal to $\frac{N^i_e}{\mu_{u,d}} + \frac{N^i_e}{\mu_{d,e}} + \frac{N^i_e}{P_e}$, while N^i_u and N^i_e become (11) and (12), respectively. As N^i becomes larger, $\frac{N^i_u}{P^i_u}$ is closer to $\frac{N^i_e}{\mu_{u,d}} + \frac{N^i_e}{\mu_{d,e}} + \frac{N^i_e}{P_e}$. Thus, $\frac{N^i_u}{P^i_u} = \frac{N^i_e}{\mu_{u,d}} + \frac{N^i_e}{\mu_{d,e}} + \frac{N^i_e}{P_e}$ is established. As a result, $\frac{\eta^i}{\Delta t^i}$ in (10) is given as:

$$\frac{N^i}{R^2(N^i)^2+(4F+t^i_{start}-t^{i-1}_{fin})RN^i+2F(2F+t^i_{start}-t^{i-1}_{fin})} \tag{13}$$

$$\left(R = T_g + T_{ng} + \frac{\mu_{d,e}P_e+\mu_{u,d}P_e+\mu_{u,d}\mu_{d,e}}{\mu_{u,d}\mu_{d,e}P_e+P^i_u(\mu_{d,e}P_e+\mu_{u,d}P_e+\mu_{u,d}\mu_{d,e})}\right)$$

To sketch (13), by differentiating it by N^i, we obtain:

$$\frac{-R^2(N^i)^2+2F(2F+t^i_{start}-t^{i-1}_{fin})}{\{R^2(N^i)^2+(4F+t^i_{start}-t^{i-1}_{fin})RN^i+2F(2F+t^i_{start}-t^{i-1}_{fin})\}^2} \tag{14}$$

When $t^i_{start} \le t^{i-1}_{fin} - 2F$, (13) decreases monotonically as the value of N^i increases and takes the maximum when N^i_{th} is N^i_{MIN}. When $t^i_{start} > t^{i-1}_{fin} - 2F$, $\frac{\eta^i}{\Delta t^i}$ is a convex function taking the maximum when N^i is $\frac{\sqrt{2F(2F+t^i_{start}-t^{i-1}_{fin})}}{R}$. Note that N^i is chosen so that the denominator of (13) does not become zero. Through the above procedures, we can obtain N^i_{th} as follows:

$$N^i_{th} = \begin{cases} \frac{\sqrt{2F(2F+t^i_{start}-t^{i-1}_{fin})}}{R} & \left(N^i_{MIN} \le \frac{\sqrt{2F(2F+t^i_{start}-t^{i-1}_{fin})}}{R}\right) \\ N^i_{MIN} & \left(\frac{\sqrt{2F(2F+t^i_{start}-t^{i-1}_{fin})}}{R} < N^i_{MIN}\right) \end{cases} \tag{15}$$

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