EVALUATION OF SATELLITE IMAGERY INTEGRATION IN OPTIMAL AIRCRAFT OPERATION PLANNING FOR DISASTER RELIEF

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Abstract

Japan Aerospace Exploration Agency has been developing an integrated aircraft operation system for disaster relief in order to aid immediate post-disaster relief operation. The system includes disaster area observation planning as part of the search and rescue process. Conventional methods rely mostly on manned aircraft in the reconnaissance phase, but here satellite imagery is considered as potential information source, too. In this research, the potential of satellite imagery in optimal aircraft operation planning is investigated. Search and rescue flow is described quantitatively and a novel rescue aircraft route optimization method is applied to simulate the initial search process. Numerical simulations for various disaster scales are conducted and the results are analyzed in respect of the time necessary for search and location of rescue needs. It is shown that depending on the size of the disaster area, there exist an optimal number of disaster aircraft which should be assigned to the initial search phase. The usage of satellite imagery is validated and it is proven that for medium and large-scale disasters satellite imagery usage shorten the time necessary to locate places with rescue needs. Satellite imagery acquisition timing is also investigated and the results are analyzed according to disaster area size and number of available aircraft.

1 Introduction

1.1 Research Background

In the aftermath of the Great East Japan Earthquake and Tsunami which struck on March 11, 2011, aircraft played a major role in the disaster relief operations [1]. In the case of a major earthquake, accessing the disaster area by air is often the only means to provide help to many wounded people and evacuees. Bad weather, insufficient reconnaissance, decision-making delays, and limited resources, however, bound aircraft operations significantly [2]. To tackle these issues, mainly focusing on real-time information sharing between aircraft and disaster relief headquarters, as well as efficient operations of rescue aircraft, Japan Aerospace Exploration Agency (JAXA) has been developing "Disaster Relief Aircraft Information Sharing Network (D-NET)" [3]. The main contribution of D-NET is establishing fast and reliable communication between ground bases and rescue aircraft, with the efficiency and usability of the system being proven in numerous disaster drills already [4]. Even though implementing D-NET in aircraft missions would improve the efficiency of rescue operations, the limited resources remain a bottleneck which is hard to alleviate. To speed up relief operations, JAXA has started the development of an integrated aircraft operation system for disaster relief (D-NET 2). This system will combine operations of satellites, unmanned aircraft and manned aircraft (mainly helicopters) in disaster relief. To the best of our knowledge, incorporating satellites in direct search and rescue together with manned and unmanned aircraft is an unprecedented endeavor not just in Japan, but also in the world.

Satellite observations have already been used to improve the response to natural disasters. SERVIR [5], developed by NASA and the US Agency of International Development, relies on a group of Earth-observation satellites to provide images used in natural disaster analysis, such as fires, for example [6]. Images from SERVIR were also used to direct rescue crew to the victims in the aftermath of the earthquake which rocked Honduras on 28 May, 2009 [7]. In this case, however, disaster assessment map based on satellite imagery was available to the relevant disaster relief agencies almost 3 full days after the earthquake struck. Such a time delay, however, can be crucial in the event of a strong earthquake, as the first 72 hours after a disaster are critical. Therefore, so far even though satellite imagery has been used for post-disaster management and humanitarian goods logistic planning [8], no involvement in direct search and rescue has been proposed. Recent research and development, though, suggest that satellite imagery can prove a valuable information source for rescue teams in the field. A major contribution is expected by the Advanced Land Observing Satellite-2 (ALOS-2), to be launched by JAXA in 2014 [9]. Three observation modes with various resolution (1 to 100m) and swath (25 to 490 km) will match the disaster area monitoring needs- wide area with a relatively lower resolution or detailed observation of a narrower area. ALOS-2 will fly over Japan twice a day and thanks to its radar observation will be possible at night and in bad weather. Furthermore, it is expected that urgent observation requests can be handled prior to an hour before the observation itself, and the final image product will be available in just a few hours, which will tremendously shorten the delay in image acquisition mentioned above. Besides, numerous international initiatives such as Sentinel Asia [10] and the International Charter [11] have been set up to assure improved prompt disaster response. Therefore, the authors believe that the timing for considering satellite imagery in direct search and rescue disaster relief system is appropriate.

1.2 Objectives

In particular, satellite imagery can be used by disaster response planning teams to identify flooded areas and land surface changes such as landslides, for example [8]. The objective of the current research is to evaluate the potential advantages and disadvantages of using satellite imagery as information source in direct disaster relief aircraft operations and the effects (if any) on optimal manned aircraft resource distribution management. This process is a part of the conceptual design of JAXA's integrated aircraft operation system for disaster relief (D-NET 2). As the system should be useful in disasters of various scales, a general model of the disaster area is considered here.

This paper is organized as follows. The simulation assumptions are described in Section 2. The problem model and optimization algorithm are discussed in Section 3. Section 4 shows the results obtained under the assumptions stated above. The paper is summarized in Section 5.

2 Simulation Assumptions

2.1 Qualitative Assumptions

2.1.1 System Overview

The operational concept of D-NET 2 is shown in Fig. 1. The system can be divided into three main components- information gathering, planning and operation.

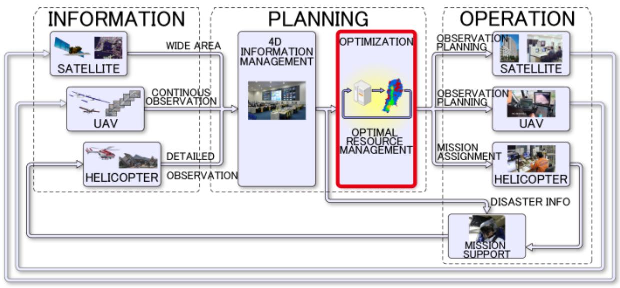

Fig. 1. Operational concept system overview

Information will be collected by satellites, unmanned aerial vehicles (UAVs) and helicopters. In this paper, only manned aircraft (helicopters in particular) and satellites are considered as reconnaissance sources, with UAVs being left a subject of future study.

The planning component of the system will consist of two parts- integrated information subsystem and optimal resource management subsystem. At present, rescue is possible only at places where search has completed, which caused delays in the rescue missions at areas with difficult access. D-NET 2, however, is going to include prediction in the information management system. Prediction will be based on information available beforehand, such as hazard map information. Such a prediction is considered in this research, as well, and is quantitatively described in detail in the next section. The integrated information subsystem will also include real-time external sources information such as weather information and hospital information, as well as real-time information from internal sources (aircraft and satellites).

Based on all of the above information, the optimal resource management subsystem is going to schedule rescue missions as to minimize the regional gap in relief operations. It has to be able to provide results in real-time, be robust, include aircraft dynamics and operational constraints, reflect uncertainty and provide easy-to-understand solutions to dispatchers, as the system is meant to be a decision-support tool not aimed at full automation. The optimal resource management component shown in red in Fig. 1 is the target of the current research.

The operation component includes tools which aid more efficient mission execution, e.g. tools for manned helicopter flight in bad weather/ night conditions, more efficient aerial firefighting, etc. All of these technologies have been under development at JAXA.

2.1.2 Search and Rescue Flow

Evaluating disaster relief operations requires a definition of search and rescue stages and their quantitative description. In this research the authors have adopted a parameter "Quality of Life" (QOL) [12] which expresses the post-disaster condition of a single area unit. Right after the disaster, QOL in all areas is 1, i.e. no information on condition and damages is available. For disaster response teams, this is the most critical condition possible. Once information has been collected and the rescue needs have been defined, the area is characterized by QOL=2. Only then can specific rescue be planned and executed (QOL=3). Full recovery is described as QOL=4.

The system scope of D-NET 2 is shown in the shaded orange area and the scope of the current paper is shown in blue in Fig. 2. Here, the authors evaluate optimal aircraft operation planning in the initial search phase only, where the implementation of satellite imagery is considered to be most efficient.

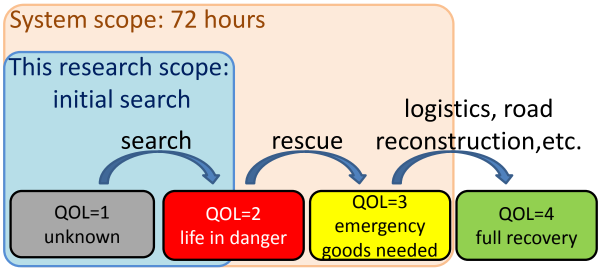

Fig. 2. QOL definition and research scope

The initial goal of search and rescue operations is to switch all areas from grey (QOL=1) to red (QOL=2) or yellow (QOL=3). For QOL=", however, rescue needs need to be thoroughly defined, i.e. not only the location, but also the number and condition of evacuees have to be known to the rescue teams. For these details to be collected, a rescue helicopter must have landed at the site at least once, considering only helicopters and satellite imagery is available for reconnaissance. Therefore, in this research we define an intermediate QOL=1.5 to characterize areas where initial search has completed and the location of the needs has been set. The search process assumed in this research is shown in Fig. 3. Here, t_{loc} identifies the time passed after the start of the search process needed to locate the rescue needs at a particular area.

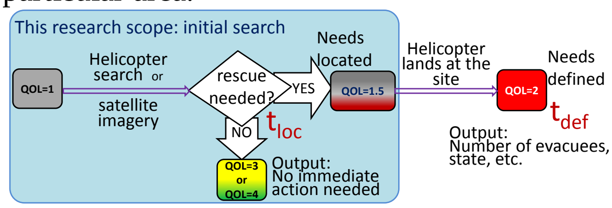

Fig. 3. Search process flow

2.1.3 Satellite Imagery Usage

A candidate satellite for the system is ALOS-2 [9]. ALOS-2 can conduct observation in spotlight, strip map or scan synthetic aperture radar modes over a wide area. Besides, observations are possible at night and in bad weather, so in this respect it excels helicopter observation capabilities. Satellite imagery has already proven effective to identify flooded areas and land surface changes such as landslides, so such applications are considered in D-NET 2 as well. At this state of our research, the usage of satellite imagery is limited to observation of coastal regions which are likely to be flooded by tsunami following a major earthquake. From previous experience and based on discussions with satellite imagery analysts, however, the authors have concluded that even though satellite imagery can be used to successfully identify areas which require rescue, even in areas where no rescue needs have been identified through satellite imagery rescue might be needed, i.e. a "rescue positive" is most probably a positive, but a "rescue negative" does not really mean a negative. This fact is behind the main satellite imagery usage in our simulation as well.

2.1.4 Rescue Need Prediction

The present disaster relief mission management is based on the "no request- no mission" rule, i.e. unless a rescue need is defined, no rescue aircraft will be sent on site. The major advantage of this principle is that it helps avoid "empty missions", i.e. missions on false alert and missions at sites where no evacuees are waiting, for example. In the case of a major disaster, though, some areas might be so badly affected that the victims there might not even be able to request help.

Besides, so far the initial search has been done very systematically without fully considering that some areas are more likely to need rescue than others. To account for this difference and allow for more efficient reconnaissance in the immediate aftermath of a disaster, the authors have introduced an urgency level parameter (UL) which shows how likely it is for rescue missions to be needed at a certain place. High UL means high likelihood probability that rescue crew should be sent on site. UL is determined based on information available beforehand, as well as information obtained in the search process and is integrated in D-NET 2 system in the information management block (Fig. 1).

2.1.5 Current Research Flow

The system has to be applicable to a wide range of disasters. Therefore, instead of simulating one particular disaster based on past data of future predictions, the authors consider disaster areas of various sizes.

The current research can be divided into two main parts. At first, the authors investigate how the time needed for initial search t_{loc} of the whole disaster area depend on the number of helicopters available. Next, in simulations reflecting the usage of satellite imagery for rescue needs allocation, the authors investigate how the initial search time t_{loc} changes compared to the case when no such imagery is available. This is done by optimal routing and assignment of aircraft.

2.2 Quantitative Assumptions

2.2.1 Disaster Area Model

The disaster area is divided into cells of a predefined size. Each cell is a 2 km x 2 km square. The overall size of the disaster area varies between 20 km x 20 km (10 cells x 10 cells) and 200 km x 200 km (100 cells x 100 cells). The results presented here are for three disaster areas representing small 40 km x 40 km (20 cells x 20 cells), medium 60 km x 140 km (30 cells x 70 cells) and large-scale 200 km x 200 km (100 cells x 100 cells) cases, each shown in north-south and east-west direction. The asymmetry accounts for Japan's geographic location. Additionally, the most east 5 rows of cells are assumed to be flooded by a tsunami.

2.2.2 Satellite Imagery Acquisition Parameters

When available, satellite images are assumed to cover the most east 10 rows of each disaster area, including the flooded coastal areas defined above.

The satellite imagery acquisition timing t_{sat} is either 1 h or 4 h after the start of the helicopter search operations, depending on the scenario.

2.2.3 Disaster Relief Aircraft Assumptions

We assume that all disaster relief aircraft are UH-1 helicopters. The average cruising speed is 100 kt and the maximum range (flight time) between two refuels is 2 h 45 min, equal to an approximate coverage of 250 cells, accounting for 10% fuel margin. Each refueling takes 30 min, equivalent to 50 cells cruising time.

Table 1. Simulation scenario parameters

	Size [cells]	Base coordinates (cell, cell)	Satellite imagery acquisition time	Disaster scale	Base characteristics (in: inside the disaster area, out: outside the disaster area)
1	20 x 20	(5,9)	1 h (100 cells)	Small	1 base in
2	20 x 20	(-9,13),(5,9)	1 h (100 cells)	Small	1 base in, 1 base out
3	30 x 70	(9,34)	1 h (100 cells)	Medium	1 base in
4	30 x 70	(4,59),(10,9)	1 h (100 cells)	Medium	2 bases in
5	30 x 70	(4,59),(10,9)	4 h (400 cells)	Medium	2 bases in
6	30 x 70	(-13,30),(4,59),(10,9)	1 h (100 cells)	Medium	2 bases in, 1 base out
7	100 x 100	(-13,30),(28,63),(40,18)	1 h (100 cells)	Large	2 bases in, 1 base out
8	100 x 100	(-13,30),(6,93),(28,63),(40,18)	1 h (100 cells)	Large	3 bases in, 1 base out
9	100 x 100	(-13,30),(28,63),(40,18),(71,49)	1 h (100 cells)	Large	3 bases in (1 base near coast), 1 base out
10	100 x 100	(-13,30),(28,63),(40,18),(71,49)	4 h (100 cells)	Large	3 bases in (1 base near coast), 1 base out

Helicopters can take off, land and refuel at any helicopter base, which location is defined for each scenario. The number of bases varies between 1 and 4, with some bases being outside the disaster area, i.e. in unaffected areas. A summary of the numerical simulation scenarios and the corresponding helicopter bases locations and satellite images acquisition time is shown in Table 1. The cells are numbered starting from top to bottom, left to right, the upper left cell being (0,0). Aircraft can move one cell at a time in the south, north, east or west direction. The time required for one move is set to one step (2 km) and is approximately equal to 36 seconds. In all simulations presented in this paper, no hovering over any areas to collect information is assumed.

2.2.4 Prediction Parameters

Each cell in the disaster area is characterized by its own urgency level (UL), as described in 2.1.4. UL=1 is set to cells with high urgency level (schools, hospitals, etc.), and UL=0 to cells with standard urgency level. Furthermore, the following probability parameters (Table 2) are defined to describe the disaster area. The first two parameters (A and B) are related to the rescue needs distribution and are needed to define the scenarios only. They do not depend on the accuracy of the available information. Varying A and B results in increasing/decreasing the number of rescue missions. If data from real disaster relief operations is used, these parameters will not be relevant, as all the necessary information will be contained in the scenario already. This is not the case with the next two parameters, C and D, however. They determine the accuracy of the needs assessment, i.e. the prediction accuracy. For example, knowing all rescue needs completely is equivalent to $\mathrm{C} = 1.0$ and $\mathrm{D} = 0.0$. To account for uncertainties, the basic values chosen here are $\mathrm{C} = 0.9$ and $\mathrm{D} = 0.2$.

Table 2. Prediction parameters definition

	Definition	Value
A	the probability that there are rescue needs in a coastal cell	0.9
B	the probability that there are rescue needs in an inland (non-coastal) cell	0.4
C	the probability that a cell with rescue need has high urgency level UL=2	0.9
D	the probability that a cell with no rescue need has high urgency level UL=2	0.2

3 Optimization Algorithm

3.1 Problem Formulation

Aircraft routing problem can be formulated as a traveling salesman problem with multiple agents and capacity constraints, or a grid-search problem. The general formulation would imply the number of nodes to be equal to the number of cells, however. For medium and large scenarios solving the problem by genetic algorithm, for example, takes a lot of computational time, however, and the results obtained are not necessarily sufficiently optimized. Therefore, in this research, a different computational method is developed.

3.2 Optimization Method

Each cell is in one of the following states:

- not checked yet
- scheduled to be checked by a helicopter
- scheduled to be checked by satellite
- checked already

A weight value S_{cell} is assigned to each cell which is determined by the state, predicted urgency UL and relative position in the disaster area. S_{cell} is determined as shown in Eq.1. Cells which are scheduled to be checked by other helicopters or satellites have low weight S_{state}, as double-checking will not bring any new information to the system. The last value S_{boundary} is introduced to avoid one single cell being left unchecked surrounded by checked cells, which would later require additional search.

$$\begin{aligned} S_{\text{cell}} &= S_{\text{state}} \times S_{\text{UL}} \times S_{\text{boundary}} \\ S_{\text{state}} &= \begin{cases} 1.0, & \text{(not checked)} \\ 0.01, & \text{(planned to check)} \\ 0.0, & \text{(checked)} \end{cases} \\ S_{\text{UL}} &= \begin{cases} 2.0, & \text{(high UL)} \\ 1.0, & \text{(low UL)} \end{cases} \\ S_{\text{boundary}} &= 1.01^{Neighbors\ Checked} \end{aligned} \tag{1}$$

Each potential route is evaluated by Eq.2. Longer routes with high weight value sum are privileged. The length of the route is set as an influencing parameter in order to reduce refueling frequency.

$$S_{\text{route}} = \frac{(\sum S_{\text{cell}})^2}{Route\_Length} \tag{2}$$

Two major route types are considered: “rectangular route” which covers all cells in a certain rectangular region, and traveling salesman problem (TSP) route, which uses some cells as nodes to solve the TSP (nodes are connected by straight route line segments).

The initial branching of the whole disaster area into rectangular blocks is done by solving such a TSP. As there are more than one possible “rectangular routes” within the same rectangle, the particular route in each case is determined as described below.

The basic idea is the “comb route”. Depending on the rectangular area size (even/odd number of cells), several variations exist, as shown in Fig. 4. Rotating the comb on 90 deg and changing the direction of the route gives 8 possible variations. Therefore, the optimal (sub-optimal) rectangular route branching and each particular route within the rectangle are determined.

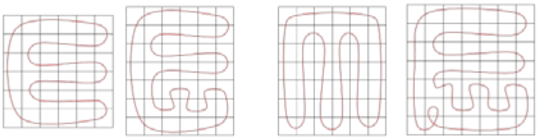

Fig. 4. Comb routes

4 Simulation Results

Numerical simulations are conducted for each scenario shown in Table 1 (10 scenarios), varying the number of search helicopter available between 1 and 10 (10 cases), and considering the lack or presence of satellite imagery (2 cases). When satellite imagery is available, cells in the coastal area are scheduled to be checked by satellite t_{sat} after the helicopter search operations begin.

Each cell is defined by its location, UL, rescue needs r (Eq.1) and t_{loc}. As seen from Fig. 3, the possible outcomes from the cell initial search are $QOL = 1.5, 3$ or 4.

$$r = \begin{cases} 0, & QOL = 3 \text{ or } 4 \\ 1, & QOL = 1.5 \end{cases} \tag{3}$$

A sample simulation input/output is shown in Fig. 5. In this particular case, a small-scale scenario No.1 is shown. The predicted urgency level distribution UL is shown in (a). Dark grey cells show high UL. The search time t_{loc} at each cell is shown in (b). Green cells are visited earlier than yellow, orange and red cells. Satellite imagery is obtained an hour after the beginning of the search, so numerous cells in the east are observed at once (shown in yellow here). The rescue needs r distribution is shown in (c). Cells with $r=1$ are shown in brown and cells with $r=0$ are shown in yellow. Here, the prediction errors described in Table 2 are also accounted for.

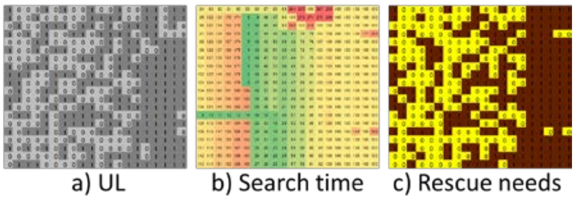

Fig. 5. Sample simulation input/output

4.1 Total Initial Search Time t_{max_all}

Total initial search time t_{max_all} is defined as t_{loc} of the last visited cell regardless of the corresponding QOL (1.5, 3 or 4 are the three possible outcomes). The results for the total initial search time t_{max_all} are shown in Fig. 6-Fig. 8 for the three disaster scales considered.

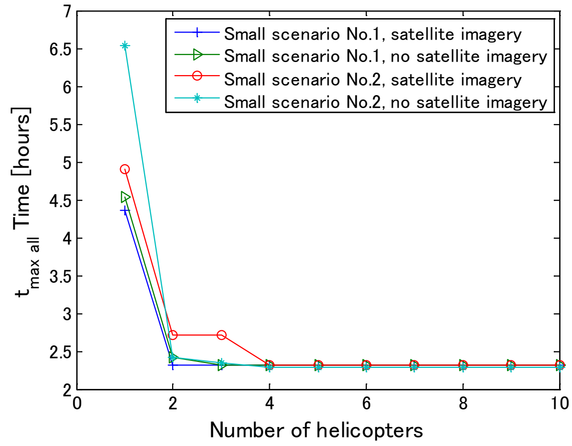

Fig. 6. t_{max_all} for small scenarios

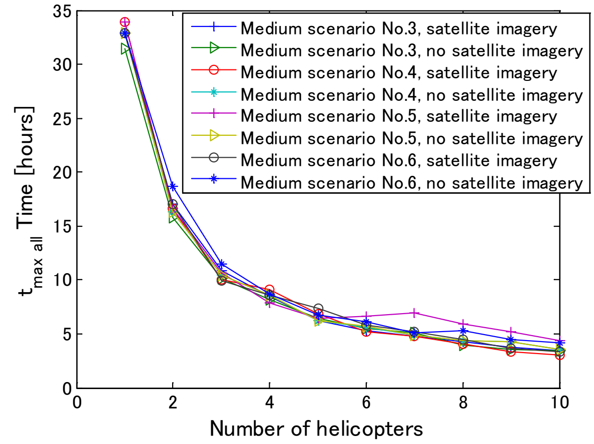

Fig. 7 t_{max_all} for medium scenarios

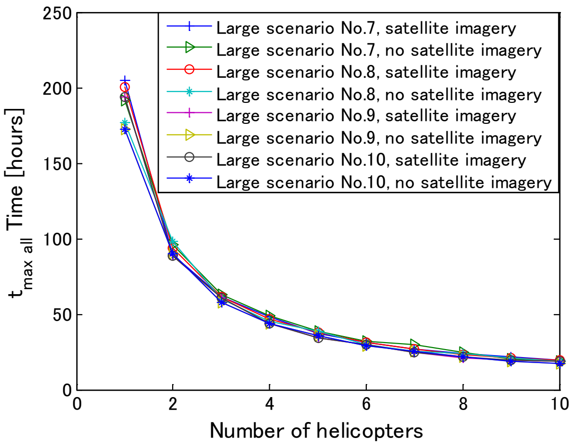

Fig. 8. t_{max_all} for large scenarios

Regardless of satellite imagery availability, for small disaster areas no change in t_{max_all} is observed with the increase of search helicopters N_{search} above 4 (Fig. 6). Besides, since t_{max_all} for N_{search}=2 and N_{search}=4 is not significantly different, it can be concluded that in these scenarios the optimal N_{search} is 2.

For medium and large scenarios, however, the decision line is not so clear. t_{max_all} decreases with the increase of N_{search} , but this decrease is not linear. In fact, the relationship between t_{max_all} and N_{search} is inversely proportional, as expressed in Eq.4, with the coefficient $C_{N=1}$depending on $t_{\max\_all}$ for $N_{search} = 1$.

$$t_{\max\_all} = \frac{C_{N=1}}{N_{search}} \quad (4)$$

Suppose $C_{N=1}$is determined as the average of all $C_{N=1}$for a certain disaster scale. In our simulations, $C_{N=1} = 30.75$ for medium and $C_{N=1} = 183.45$ for large scenarios . Results suggest that each helicopter is assigned observation area of more or less similar size and even though the exact area depends on the UL of the cells, the overall area distribution is somewhat even.

4.2 Search Time for Cells with Rescue Missions t_{max_rescue} and t_{ave_rescue}

Total search time and average search time for cells where rescue is required (QOL=1.5) t_{max_rescue} and t_{ave_rescue} are defined as shown in Eq.5. Both are important parameters as they are related directly to the next stage of the search and rescue process, i.e. rescue teams are sent to specific cells only after rescue needs are confirmed in the initial search. Furthermore, t_{ave_rescue} can be used to describe "fairness" to all cells in the disaster area, and being fair to all is a main goal of D-NET 2 resource management, as described in the introduction.

$$\begin{aligned} t_{\max\_rescue} &= \max(t_{loc}, r = 1) \\ t_{ave\_rescue} &= \text{ave}(t_{loc}, r = 1) \end{aligned} \quad (5)$$

T_{max_rescue} and t_{ave_rescue} depend on the simulation parameters set in Table 2. The general trend of t_{max_rescue} is similar to that of t_{max_all}, so here only the results for large-scale scenarios are shown (Fig. 9).

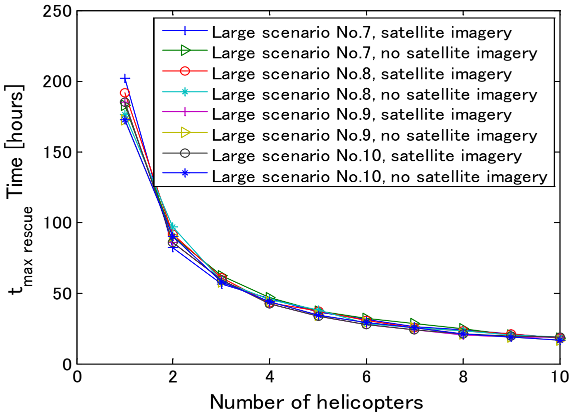

Fig. 9. t_{max_rescue} for large scenarios

The most important characteristic is the average t_{loc} for cells with rescue needs. The way the search routes are chosen here suggest that rather than minimizing the total search span, or the search span for cells with rescue needs $t_{max\ rescue}$, the search is optimized to minimize the average time $t_{ave\ rescue}$. As seen from Eq.2, the routes are evaluated based on the sum of weight values of the visited cells, without accounting explicitly for the timing when the last cell with rescue needs is visited. Results for $t_{ave\ rescue}$ are shown in Fig. 10. A seen from the figure, the general trend resembles that of $t_{max\ rescue}$.

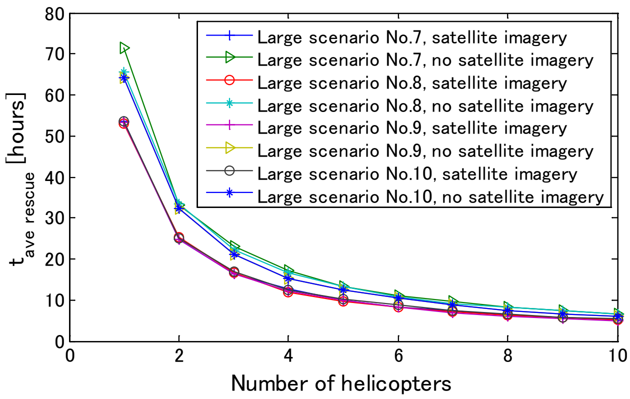

Fig. 10. t_{ave_rescue} for large scenarios

As seen from the figures, the base number and location does not influence significantly t_{max_rescue} and t_{ave_rescue}, so below only the results from Scenario 7, with no satellite imagery available are discussed. For each number of helicopters available the optimization was run 5 times and the average values are determined.

Results for (t_{max_all} -t_{max_rescue}) are shown in by the blue line in Fig. 11. To examine the influence of preliminary information UL two additional simulation series are conducted where full knowledge of the needs location is assumed and where relative low-quality preliminary information is assumed. This is equivalent to [C = 1.0 and D = 0.0] and [C = 0.5 and D = 0.5] from Table 2. Based on these results, two major conclusions can be made. First, in all scenarios the better knowledge of the needs location has decreased the time necessary for reconnaissance of these cells. Next, generally speaking, as the number of available aircraft for search N_{search} increases, the difference between t_{max_all} and t_{max_rescue} decreases, so UL is relatively more important for cases with severely constrained N_{search}. The irregularities seen for simulations with 6 and 7 vehicles are thought to be due to the insufficient number of runs, but the exact reason is to be explored in further research.

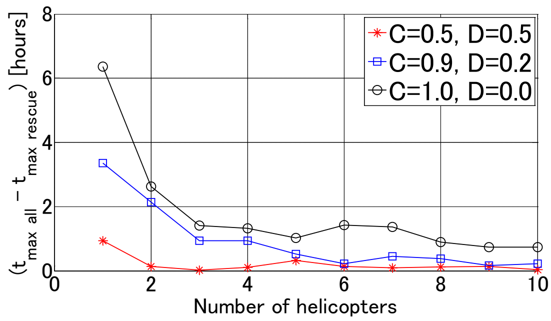

Fig. 11. t_{max_all} -t_{max_rescue} for Scenario 7, no satellite imagery

As mentioned above, rather than t_{max_rescue}, t_{ave_rescue} is of interest if fairness to all is to be the main factor determining the optimal resource management in the system. Here, we examine how the average time for allocating rescue needs changes in respect to the prediction parameters C and D. The results are shown in Fig. 12. These graph shows the values for ($t_{ave\_rescue\_C=0.9,D=0.2}$ - $t_{ave\_rescue\_C=1.0,D=0.0}$) [hours] shown in blue and ($t_{ave\_rescue\_C=0.5,D=0.5}$ - $t_{ave\_rescue\_C=1.0,D=0.0}$) [hours] shown in red. Accurate needs prediction decreases significantly t_{ave_rescue}, but as the number of available helicopters increases prediction information value decreases, i.e.

more vehicles can somewhat compensate for inaccurate predictions.

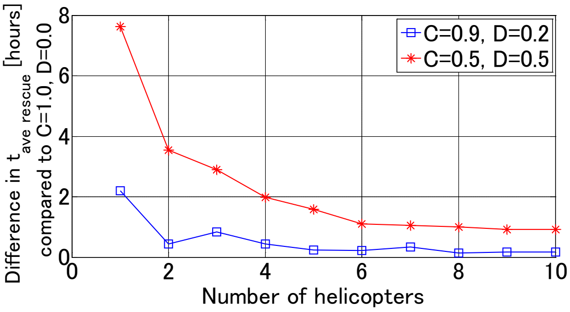

Fig. 12. Comparison of t_{ave_rescue} for two prediction scenarios

4.3 Satellite Imagery

The influence of satellite imagery availability is investigated by t_{ave_rescue} (Fig. 13-Fig. 15) for each scenario with and without the presence of satellite imagery. Positive values show how much time [h] is gained by using satellite imagery in each case, e.g. in Fig. 14, Scenario No.2, when 2 helicopters are available for search operations, using satellite imagery shortens the average time necessary to locate the cells with rescue needs by 1h 12min. As seen from the graphs, however, generally speaking, this time gain decreases as the number of search helicopters increases.

For small scenarios, using satellite imagery for rescue needs detection slows down the reconnaissance process when more than two helicopters are available (Fig. 13). For medium and large-scale disasters, t_{ave_rescue} decreases when satellite imagery is used. An exception occurs when the satellite imagery acquisition time t_{sat} is relatively late (medium scenario No.5). In our simulation two possible values for t_{sat} are considered- 1h (Scenario No. 1-4, 6-9) and 4h (Scenario No. 5 and 10). As seen from Fig. 14, in Scenario No.5 when N_{search}>4, rescue needs are on average identified faster when no satellite imagery is used. When the search area is wider, though, even delayed satellite imagery is better than no satellite imager (Scenario No. 10 in Fig. 15). This result is partly due to the current assumption about the usage of satellite imagery explained in detail in Section 2.1.3, and mainly that a "rescue positive" obtained via satellite imagery is most probably a positive, but a "rescue negative" does not really mean a negative and needs further confirmation by helicopter search.

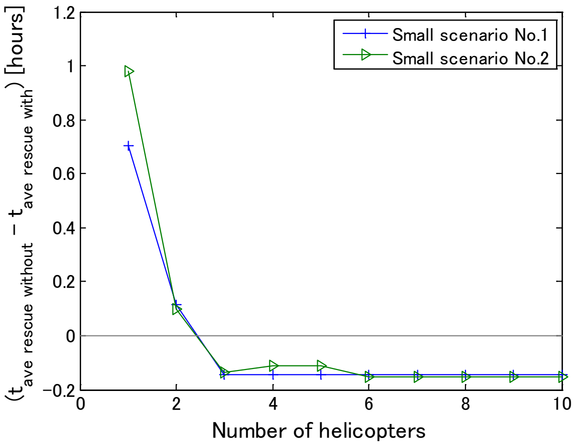

Fig. 13. t_{ave_rescue} time gained by using satellite imagery for small scenarios

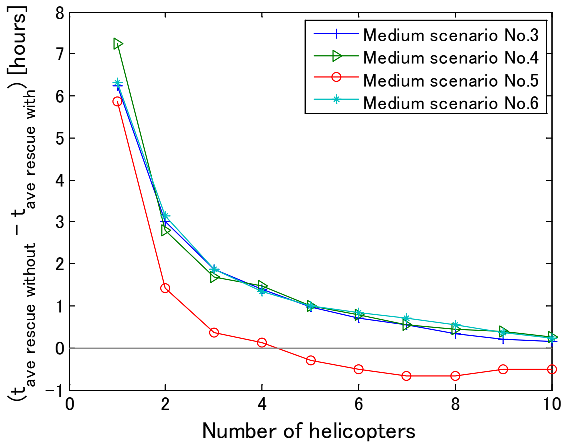

Fig. 14. t_{ave_rescue} time gained by using satellite imagery for medium scenarios

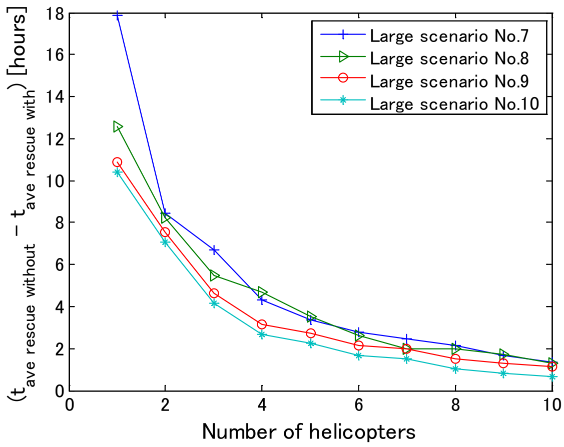

Fig. 15. t_{ave_rescue} time gained by using satellite imagery for large scenarios

5 Conclusions and Future Work

In this research, potential integration of satellite imagery in direct post-disaster search and rescue aircraft operation planning was considered. Optimization method for route planning of disaster relief helicopters was developed and numerical simulations for various disaster scenarios were conducted. The results led to four main conclusions. First, there exist a semi-optimal number of helicopters which should be involved in the initial search, as further increase in this number does not significantly change the required search time necessary to explore the whole disaster area. Second, by estimating the total search time needed when a single aircraft is in operation, an approximate evaluation of the search time when more aircraft are involved can be done. Third, satellite imagery is, generally speaking, beneficial for allocation of rescue needs, especially for large disaster areas. Late imagery acquisition, however, might slow down the rescue need location process, so caution is needed. Furthermore, analysis on the quality of rescue needs prediction information showed that accurate assessment can significantly speed up the reconnaissance process. This implies another possible application of satellite imagery, not considered so far- more accurate needs location prediction done real-time based on satellite imagery information. Future work will include such dynamic predictions, as well as Monte-Carlo simulations for the scenario analysis which might give valuable insights into improved search optimization algorithms. Further analysis is necessary to determine all optimization parameters, but at this stage it can be concluded that satellite imagery are beneficial for direct post-disaster search when used appropriately.

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