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INTEGRATED UAS TRAJECTORY OPTIMIZATION FOR DISASTER RESPONSE RECONNAISSANCE MISSIONS

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Abstract

The disaster response domain has experienced an increased focus in recent years. As part of this focus, JAXA and NASA have been collaborating on the integration of manned and unmanned aircraft in support of disaster response operations through integrated testing of their respective mission planning and optimization system (Disaster Relief Aircraft Information Sharing Network, or D-NET) and a UAS traffic management (UTM) system. This work details a small unmanned aircraft system (sUAS) trajectory optimization algorithm applied to immediate disaster reconnaissance and its integration with D-NET and UTM to aid strategic mission planning. Joint simulations were performed in December 2019 with results that showed the flight trajectory optimization, as it was applied, improved efficiency. Results also highlighted the need for the ability to identify and resolve potential conflicts due to the increased number of aircraft needed in the same airspace. This additional level of deconfliction was implemented in the simulation and was achievable by incorporating information provided by UTM to replan the trajectories in concert with D-NET. The joint simulations demonstrated the interoperability between two systems (D-NET and UTM) and highlighted the potential for future applications in broader contexts of Advanced Air Mobility (AAM).

Keywords: disaster response, airspace management, mission planning, optimization, interoperability

1. Introduction

Natural disasters require safe and efficient response. Immediate post-disaster operations include various missions such as reconnaissance, search and rescue, and the transport of people, medical, and food supplies. Damaged infrastructure can limit ground access to disaster-hit areas, which requires alternative disaster response means. Manned aircraft have traditionally been involved in such operations, but recently small unmanned aircraft systems (sUAS) have been in the spotlight as they can provide low-cost yet efficient support to disaster responders. There are already numerous examples of sUAS applications in disaster responses, ranging from reconnaissance missions, medical supply deliveries to firefighting applications [1]. These examples illustrate the potential of sUAS to aid disaster response. There are, however, numerous technical challenges as well. First, sUAS cannot operate in the same airspace as manned aircraft, as situational awareness and information sharing are limited. Safe operations require mutual sharing of flight intent and telemetry. NASA and JAXA have been collaborating through a joint agreement to explore the application of their respective UTM and D-NET systems to address this challenge. Details of that effort are highlighted in past research [2], [3]. A second challenge is that large-scale disasters require multiple vehicles whose mission assignments and trajectory planning cannot be performed manually by dispatchers and need decision-support technologies. This work addresses the latter technical challenge. In particular, we focus on sUAS reconnaissance missions and propose a trajectory optimization algorithm to maximize the area covered by reconnaissance in a 24-hour post-disaster period. The novelty of the proposal lies in the integrated nature of the optimization- two independent systems (JAXA's D-NET and NASA's UTM) are connected real-time to assure safe and efficient strategic planning of sUAS reconnaissance missions. This work describes:

1. A sUAS trajectory optimization algorithm developed for real-time optimization of large-scale reconnaissance missions, and
2. A system integration test performed in December 2019, in which JAXA's D-NET and NASA's UTM were connected in real-time to optimize and verify the flight trajectories of over 80 flights to perform reconnaissance missions in a disaster-model area in Ehime, Japan.

2. Background

The goal of this research is to verify sUAS trajectory optimization and modification technology when applied to large-scale disaster reconnaissance missions. While the research is focused on pre-departure flight trajectory planning, the fast computational times and real-time connection between JAXA's D-NET and NASA's UTM make the technology applicable in tactical planning as well.

2.1 Reconnaissance Missions and Their Role in Disaster Response

Disaster response often involves a wide variety of aircraft assets, performing missions such as reconnaissance, search and rescue, and transport of goods and personnel. The reconnaissance stage is essential for the following search and rescue, as it provides rescuers with information on victim location, status, and is the key for further mission allocation and planning. Traditionally, when ground infrastructure is damaged, manned aircraft like helicopters are used in reconnaissance missions, but recent technology advances have shown the potential of sUAS as well. sUAS can be used to conduct operations using see and avoid when the sUAS is within visual line of sight (VLOS) of the UAS operator. However, beyond visual line of sight (BVLOS) operations are conducted primarily by the use of instruments but may not be required to operate under IFR. According to the FAA UAS Traffic Management (UTM) Concept of Operations (ConOps) [5], UAS operating below 400 ft can provide an operation volume that declares the area and times of intended operation. UTM uses the operation volume to support strategically deconflicting an intended operation with other operations in the airspace. This concept can be applied to large-scale reconnaissance missions, as discussed in this work.

2.2 UAS Traffic Management (UTM)

The objectives of UTM are to enable a safe and scalable approach to support the use of small UAS operations at low altitude, providing flexibility in use of the airspace where possible and structure where necessary. An architecture was developed to support UTM operations (see Figure 1), and, along with the concept, the integration of public safety entities and their operations into the UTM ecosystem has been a focus of research throughout NASA's UTM Project and beyond. The UTM technology development and assessments focused on a common situation awareness display, airspace deconfliction, operation prioritization, and coordination of dynamic changes to operation intent. These capabilities support the extension of the UTM concept and technologies to disaster response efforts and provide the necessary coordination and situational awareness to facilitate a more efficient response.

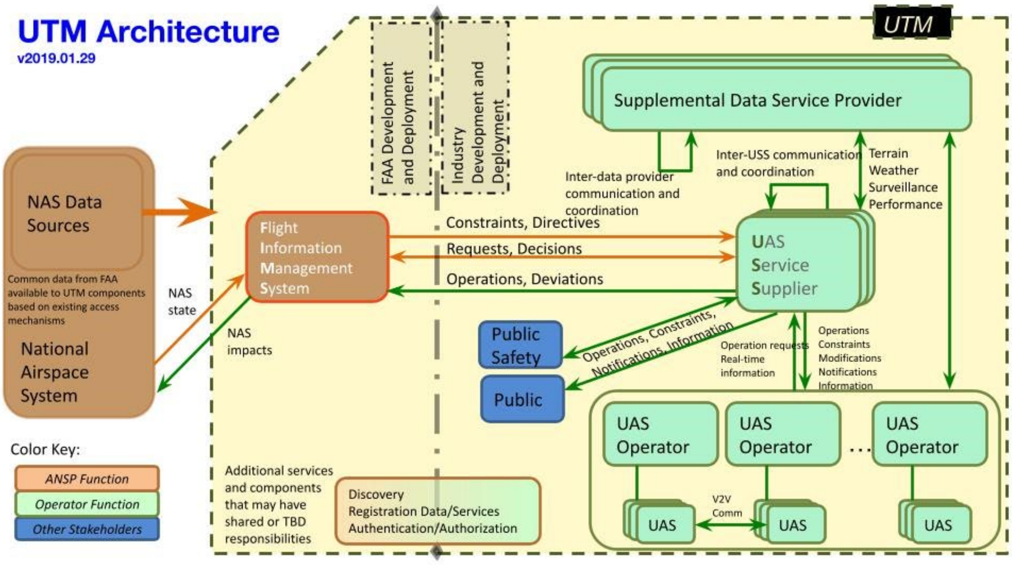

Figure 1 - UTM Architecture (note the Public Safety component in blue)

One particular extension of UTM useful in addressing is the ability to optimize–at scale–planned trajectories and operational areas with real-time input to the operator/manager regarding the current and planned state of the airspace. This extension not only benefits airspace management in disaster response, but it also potentially provides a framework that would benefit other related areas such as Advanced Air Mobility (AAM).

2.3 Disaster Relief Aircraft Information Sharing Network (D-NET)

As a means to increase aircraft safety and mission efficiency during disaster response, the Japan Aerospace Exploration Agency (JAXA) has developed the Disaster Relief Aircraft Information Sharing Network (D-NET). The D-NET system assists in the collection and sharing of disaster information through the integrated operation of aircraft, such as helicopters, sUAS, and satellites. The objective of D-NET is to efficiently acquire data from multiple sources, analyze the data, and provide optimal resource allocation and flight plan trajectories, which can be integrated in the planning and execution of rescue and response operations. D-NET is designed as a portable system for aircraft operation management in the immediate aftermath of a large-scale disaster. It consists of three main blocks: 1) data/information acquisition block, 2) optimal planning block and 3) operation execution block, as shown in Figure 2. More details on D-NET's operation concept and implementations can be found in our past publications [6]. This research utilizes D-NET's optimization module to generate sUAS flight trajectories in order to minimize the necessary reconnaissance time preceding search and rescue in immediate post-disaster operations.

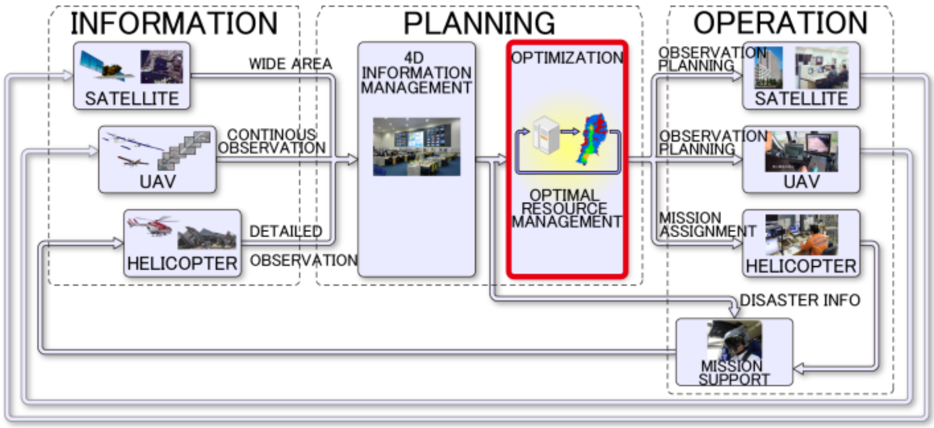

Figure 2 – D-NET system blocks

3. Reconnaissance Trajectory Optimization Algorithm

3.1 Initial Optimization Algorithm

Disaster areas are often represented as cells, which in turn are modeled as notes used for reconnaissance vehicle trajectory optimization. Such representation often results in a very large-scale optimization problem in which brute force approaches are not feasible. Therefore, to reduce computational time, the optimization in D-NET breaks down the problem into multiple steps:

Step 1. Clustering of the disaster area cells (nodes)

Step 2. Generating flight routes within each cluster

Step 3. Accounting for constraints such as battery recharging time and any vehicle maintenance time

Step 4. Finalizing the flight routes

Each step is briefly discussed below.

Step 1. Clustering of the disaster area cells

Each cell is considered as a node. All neighboring nodes are connected, so the entire disaster area is modeled as a graph. Clustering of the disaster area cells can be determined by solving a graph partition problem. The METIS library is used for determining the appropriate cluster number. [7]

Step 2. Generating flight routes within each cluster

Once the clusters are determined, the flight route within each one is generated. For simplicity, first, consider the following four potential routes:

a) Start from the most northwest cell in the cluster and move east, then move one cell south and move west, next move another cell south and move east, etc.

b) Start from the most northeast cell in the cluster and move west, then move one cell south and move east, next move another cell south and move west, etc.

c) Start from the most northwest cell in the cluster and move south, then move one cell east and move north, next move another cell east and move south, etc.

d) Start from the most southwest cell in the cluster and move north, then move one cell east and move south, next move another cell east and move north, etc.

The path along each of the four routes discussed above is calculated and the shortest one is chosen as the flight route for each cluster. The actual algorithms also consider movement in the northeast, northwest, southeast and southwest directions, but the overall logic remains similar to the one described above.

Step 3. Accounting for constraints such as battery recharging time and any vehicle maintenance time

The time to recharge the batteries and vehicle maintenance is reflected in the simulation to assure real-life operability.

Step 4. Finalizing the flight routes

Once the flight routes within each cluster are determined, the final route of each aircraft is decided as a combination of clusters that meet the flight endurance (flight range) capacity constraint posed on each sUAS. Therefore, each sUAS can visit multiple clusters.

3.2 Re-optimization based on UTM feedback

The optimal route for each vehicle is determined sequentially. For example, the optimal route for the first sUAS is calculated in D-NET and submitted as an operation to UTM. Each operation plan submitted to UTM consists of multiple 4-dimensional segments. D-NET optimization considers space provision constraints to avoid close contact among sUAS, but these constraints are not necessarily the same as those considered in UTM, which may be more conservative to account for uncertainties. If the systems operated independently and in isolation, this double-layer flight route planning could be seen as two different sUAS operators, where one of the operators or operatory systems might not be acknowledging the safety constraints of the other. However, the feedback loop designed into the planning process combines the two systems into a whole that is greater than the sum of its individual parts providing the desired airspace efficiency built upon the layers of safety each system provides. The optimization logic and integration flow are shown in Figure 3.

The entire process from the optimization within D-NET through the submission via DLinkUTM and UTM response handling is automated, which dramatically reduces the time it would take to be done manually.

A sample geography of a rejected operation is shown in Figure 4. The geographies of these two operations overlap only at one point (shown in black), which is accepted by D-NET's optimizer. Both volumes overlap temporally, so UTM rejects the operation submitted second (magenta) and provides the reason for rejection (volume overlap with the mission shown in blue).

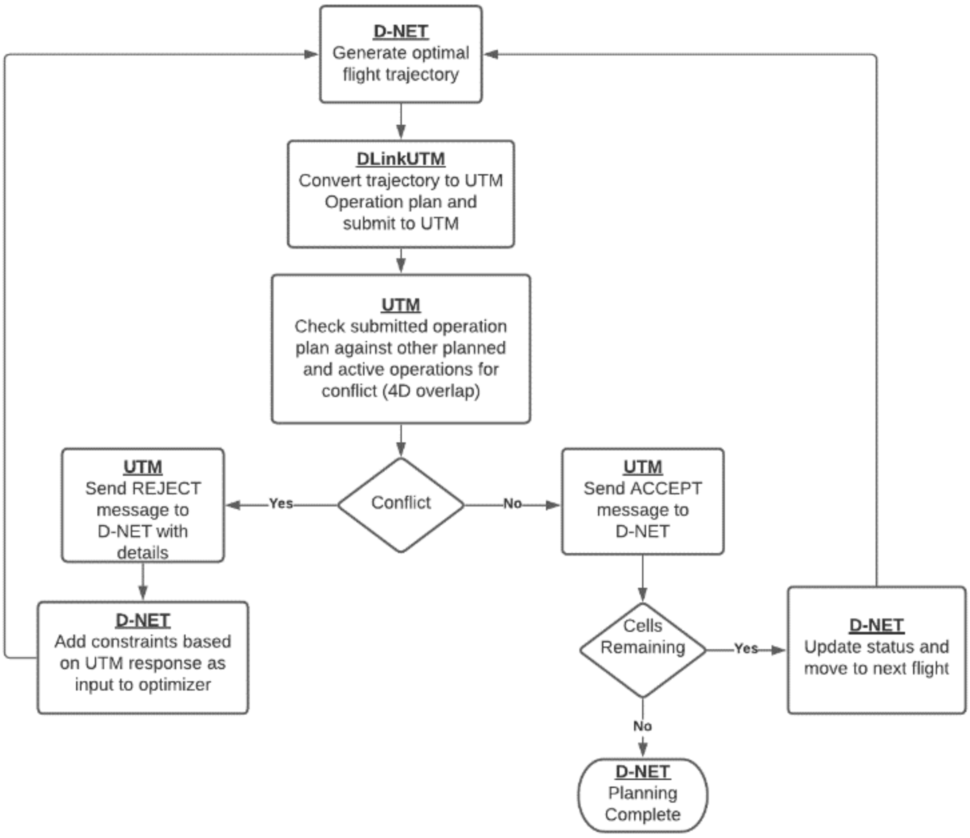

Figure 3 – D-NET and UTM interaction flow

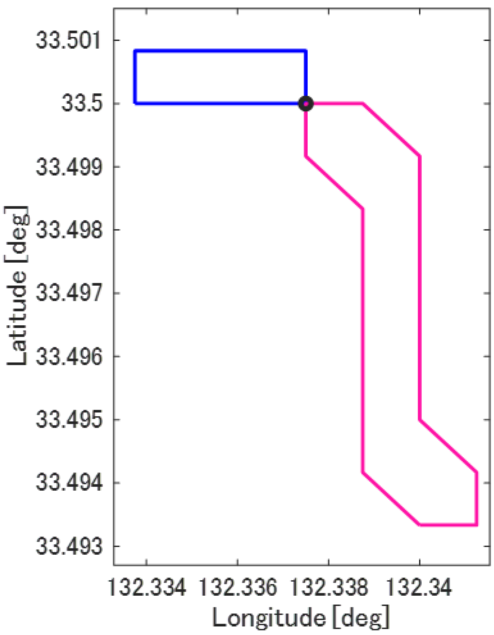

Figure 4 – Sample rejected operation

4. Simulation Testing and Results

4.1 Test Settings

Figure 5 depicts the test settings and data flow between the D-NET and UTM systems. In this simulation test, D-NET's optimizer, based in Japan, was responsible for resource allocation, mission assignment, and route generation. The operation volumes were generated from the D-NET routes and sent to UTM's server in the US where necessary feedback was obtained. The above data flow configuration allowed for real-time communication among all participants with minimal observed latencies, highlighting the global applicability of the system architecture as tested.

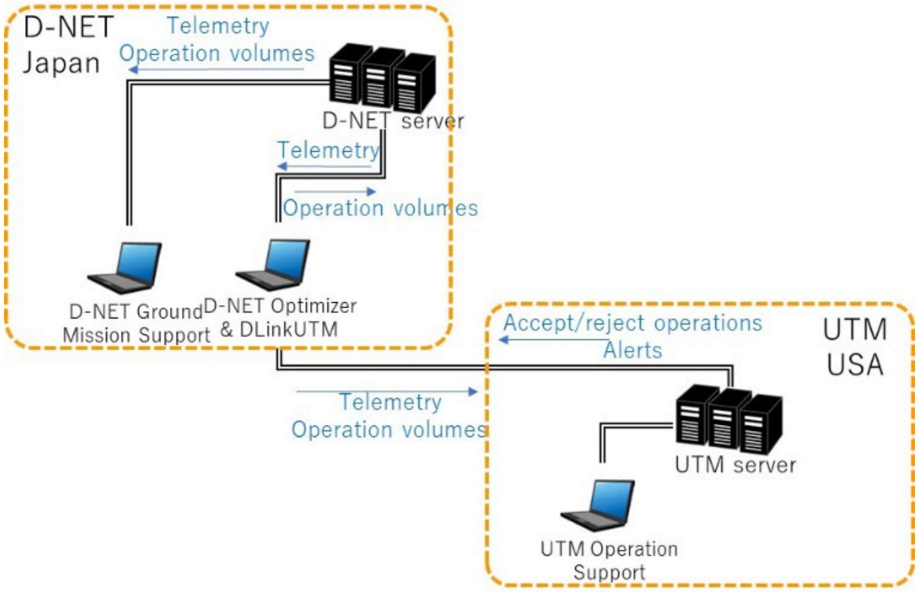

Figure 5 – Simulation test architecture

4.2 Simulation Assumptions

The disaster area was represented as a collection of identical square cells 1 km on each side. The simulations presented here were based on a model area of Ehime Prefecture, Japan. No fly zones were also included in the model. Discretization of the search area resulted in a total number of 1180 cells to be searched. The simulation assumed the availability of 6 sUAS with a flight endurance of 30 minutes each. All vehicles take off and return to the same base. The total reconnaissance time is limited to 24 consecutive hours.

4.3 Visualization Tools

A visualization tool was developed to track the progress of the optimization process and data exchange between D-NET and UTM. A sample screenshot is shown in Figure 6. In the upper right corner, the status of each sUAS and its flight number can be confirmed via DLinkUTM. In this example, the first flights for sUAS 1, 2, and 3 have been accepted. The unique flight identification number (GUFI) is also seen on this screen. Flights 4 to 6 are shown as closed, since the system shows the last known status of each vehicle and this information has remained from previous testing. The optimizer's output is seen in the bottom right corner. Reconnaissance progress statistics such as the number of remaining cells (1103 out of 1180) for example, are shown in the upper right corner. Detailed status is shown in the "Notifications" field. The map represents the target area, cells already assigned (blue), and current operation being considered by UTM (green).

The operation submission process was also tracked in real time on UTM's end in the US, as seen in Figure 7. This dual-confirmation approach showed that D-NET and UTM could successfully communicate with each other despite their remote locations and both teams in Japan and US were aware of the status of the operations.

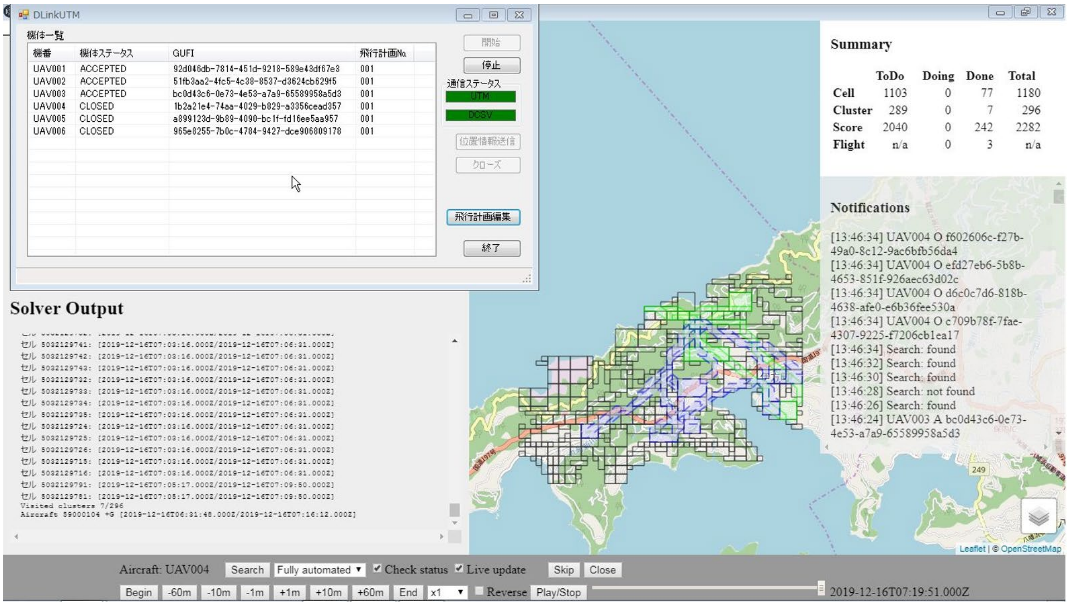

Figure 6 – D-NET visualization tool screenshot

Figure 7 – UTM visualization tool screenshot

4.4 Simulation Results

The developed D-NET/UTM integrated simulation was designed for application in strategic disaster response planning as it allows the responders to estimate what percentage of the disaster area will be covered within a certain time threshold. It also shows the areas where reconnaissance would be completed (navy clusters) and where reconnaissance is in process (pink clusters), as seen in Figure 8 - 12. The figures below show the progress at 0h, 6h, 12h, 18h and 24h after the start of the reconnaissance. The respective area coverage is 0, 418 cells (35%), 794 cells (67%), 1030 cells (87%) and 1118 cells (95%).

The total simulation time for the entire optimization process was 64 minutes in which a total of 86 sUAS reconnaissance operations were successfully planned and deconflicted.

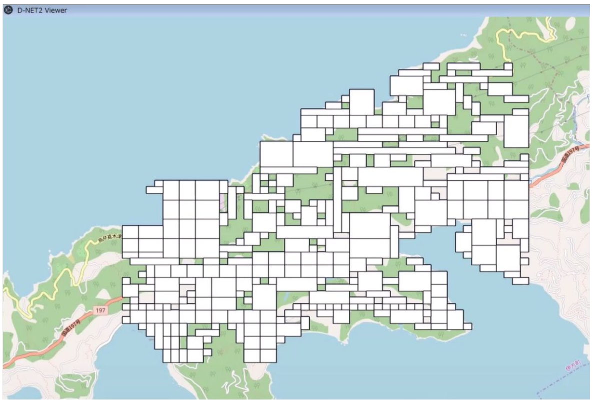

Figure 8 - Reconnaissance coverage at reconnaissance start (0%)

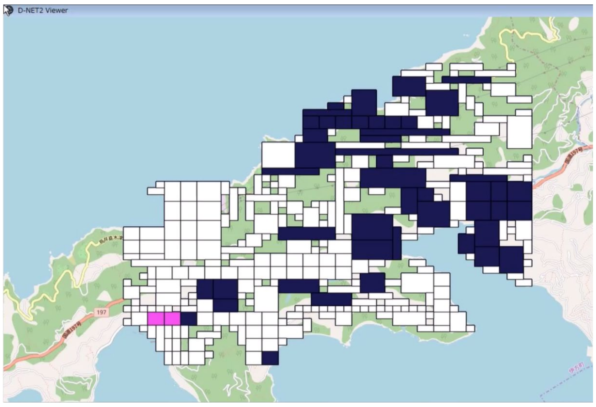

Figure 9 - Reconnaissance coverage 6 hours later (35%)

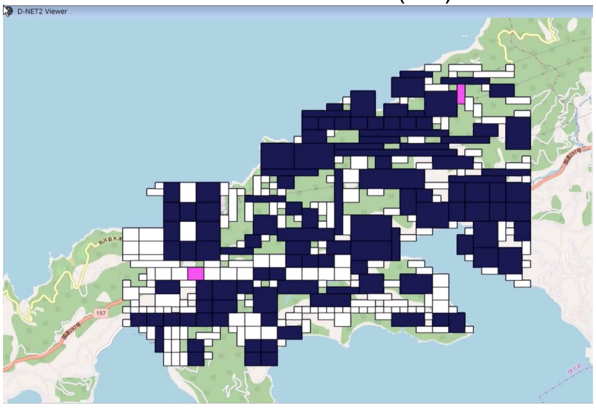

Figure 10 - Reconnaissance coverage 12 hours later (67%)

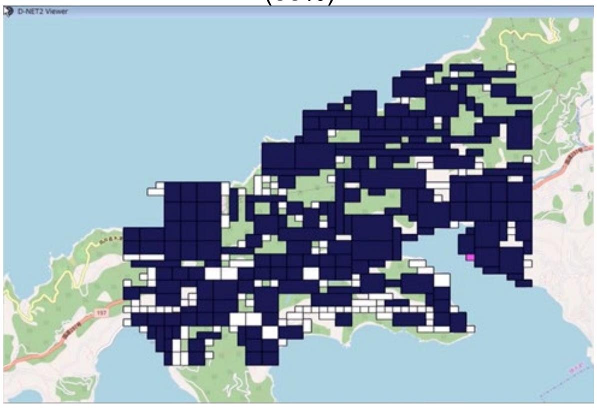

Figure 11 - Reconnaissance coverage 18 hours later (87%)

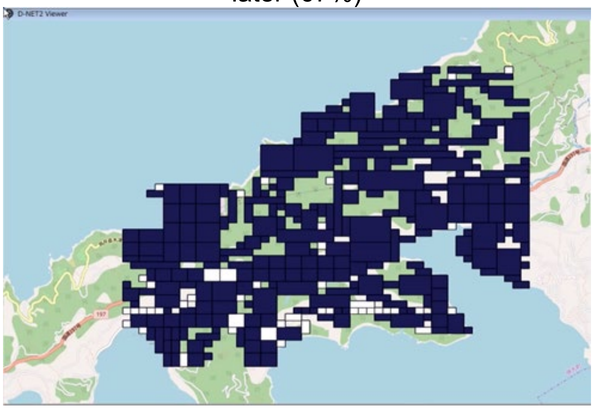

Figure 12 - Reconnaissance coverage 24 hours later (95%)

5. Concluding Remarks

The use of sUAS and other new entrant vehicles will complement the current approach to air asset deployment and applications in disaster response situations. This development will greatly enhance the effectiveness of the overall response effort by providing more targeted, tailored mission options better suited to different vehicle types and better situation awareness provided by the augmenting deployments. However, with such an opportunity comes the potential for greater complexity as more aircraft may be in use and integrated into the same operating areas. JAXA and NASA have demonstrated the feasibility and utility of integrating crewed and uncrewed aircraft in support of disaster response through the interoperability of their respective D-NET and UTM systems, which was shown to provide common situation awareness of crewed and uncrewed pilots as well as planners.

Following the establishment of that foundation, a need was identified from an operator's perspective for the ability to optimize the planned trajectories and operating areas of multiple sUAS that accounts for other airspace users (active and planned, crewed and uncrewed) and dynamic changes to the operating environment. To address this need, an optimization algorithm was tested that leveraged the capabilities of the UTM and D-NET systems to develop, optimize, and vet operating areas for 86 sUAS within a common, shared airspace. This advancement holds promise for the ability to more safely and effectively integrate a greater diversity of operations and vehicle types into the disaster response ecosystem and even has the potential for further applications in civil airspace with the advent of AAM and its need for similar capabilities as demonstrated through NASA's and JAXA's collaborative work.

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7. Copyright Statement

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