Operational Testing of Unmanned Aircraft System Traffic Management in Disaster Response

Adriana Andreeva-Mori,* Daisuke Kubo,† Keiji Kobayashi,‡ and Yoshinori Okuno§
Japan Aerospace Exploration Agency, Tokyo 181-0015, Japan
and
Jeffrey Homola,¶ Marcus Johnson,** and Parimal Kopardekar††
NASA Ames Research Center, Moffett Field, California 94035

https://doi.org/10.2514/1.D0245

In October 2018, a flight test, which occurred as part of a large-scale disaster drill in Ehime Prefecture, Japan, successfully demonstrated that the Integrated Aircraft Operation System for Disaster Relief (D-NET) and Unmanned Aircraft System Traffic Management (UTM) can contribute to the safe and efficient use of airspace by both manned and unmanned aircraft. This paper presents the technical challenges of operating unmanned aircraft in disaster relief as well as traffic management integration and the technical solutions developed to address these challenges. The scenarios used to test the integration of both systems in a real-world context, together with flight tests results and analysis, are also shown. The flight tests successfully demonstrated the application of unmanned aircraft to disaster response and showed they can safely cooperate with manned aircraft to improve response efficiency.

I. Introduction

DAMAGED ground infrastructure and vast disaster areas make the use of aircraft, both manned and unmanned, crucial for efficient disaster response. Aircraft and vehicle allocation, mission planning, and execution are usually managed by dispatchers at operation command centers set at local government or national levels. In cases of a large-scale disaster, however, human dispatchers and controllers need decision-support tools to manage limited resources safely and efficiently. Japan Aerospace Exploration Agency (JAXA) has been developing a system to manage resource allocation and provide real-time connections between aircraft and command centers during immediate postdisaster relief, and to optimize the application of available assets (D-NET) [1]. NASA has been engaged in research to enable a safe, scalable, service-based approach to airspace management of small unmanned aircraft system (UAS) operating at low altitudes under 400 ft as part of the UAS Traffic Management (UTM) project [2]. Since 2016, JAXA and NASA have partnered to investigate the integration of UAS in disaster relief operations. In October 2018, a flight test, which occurred as part of a large-scale disaster drill in Ehime Prefecture, Japan, successfully demonstrated that the coordination between D-NET and UTM can contribute to the safe and efficient use of airspace by both manned and unmanned aircraft. Connecting the two remote systems (D-NET and UTM) in real-time validated the mobility of the concept, which was an unprecedented endeavor to date. The benefit and applicability of UTM to the incorporation of UAS in disaster response efforts was also shown through data exchanges between D-NET and the aircraft operators. Prior work discussed the concept of integration between D-NET and UTM systems [3]. This paper will present the following:

1. Technical challenges in UAS integration for disaster relief, including review of current technologies and research
2. D-NET/UTM integration and technical solutions developed
3. The scenarios developed to test the integration of D-NET and UTM in a live environment
4. Flight test: execution and results

II. Technical Challenges

A. Current Technologies Available and State-of-the-Art

Over the years, the use of UAS in support of disaster response efforts has progressively become a more accepted practice. For example, during Hurricane Katrina in 2005 the southern United States experienced severe flooding [4] and deployed small UAS to the areas affected by the storm to support search and rescue operations, reconnaissance, and damage inspection [5]. Years later, during Hurricane Harvey along the Texas and Louisiana coasts in 2017 and Hurricane Florence along the North and South Carolina coasts in 2018, the emergency response operations saw an increased use of UAS and an advancement of technologies to aid in response efforts as well as greater levels of coordination across response agencies. UAS application to disaster response operations has seen global adoption and specifically has been explored in Japan. For example, Japan Ground Self-Defense Forces used commercial off-the-shelf (COTS) small UAS for damage assessment of dam structures just after the Hokkaido Eastern Iburi earthquake in 2018 [6]. The firefighting department used specially developed industrial small UAS for search and rescue missions following the Nasu avalanche disaster in 2017 [7]. The Japan Geographical Survey Institute has also used their small UAS for damage assessment and mapping of landslides in multiple earthquake and heavy rain disasters. However, these missions were done after manned aircraft missions completed and in temporary, segregated airspace. To the best of the authors' knowledge, no integrated operations of manned aircraft and small UAS through digital coordination have been conducted in actual disaster response situations in Japan. In the case of very large-scale disasters, the number of reconnaissance and search and rescue missions exceeds the number of available resources (i.e., aircraft). Adding UAS to the disaster response fleet can relieve some of the pressure on manned aircraft. Furthermore, coordinating manned and unmanned aircraft missions can speed up reconnaissance process, thus reducing the

Presented as Paper 2020 at the AIAA SciTech 2020 Forum, Orlando, FL, January 6–10, 2020; received 18 November 2020; revision received 17 May 2021; accepted for publication 25 May 2021; published online 6 July 2021.

*Researcher, Next Generation Aeronautical Innovation Hub Center.
†Associate Senior Researcher, Next Generation Aeronautical Innovation Hub Center. Senior Member AIAA.
‡Senior Researcher, Next Generation Aeronautical Innovation Hub Center.
§Manager, Next Generation Aeronautical Innovation Hub Center.
¶Unmanned Aircraft System Traffic Management Integration and Testing Lead, Unmanned Aircraft System Traffic Management. Member AIAA.
**Deputy Project Manager, Unmanned Aircraft System Traffic Management.
††Principal Investigator, Unmanned Aircraft System Traffic Management. Associate Fellow AIAA.

regional gaps in the relief operations and minimize the number of casualties.

In current-day operations, manned and unmanned vehicles are coordinated by dispatchers at disaster response command centers that are set up on short notice by local prefectural governments. Disaster response aircraft are involved in various missions, such as general reconnaissance, search, rescue, and transportation of personnel and goods. When the disaster is not spread over a large area, the relatively fewer number of response vehicles involved allows the dispatchers to maintain situation awareness and assign the most appropriate mission to each vehicle while tracking mission progress. However, as the scale of the disaster grows, human controllers need a decision support system to aid in the management of available resources safely and optimally. Even in such a case, however, when aircraft belong to different organizations (e.g., Japan Self-Defense Forces, fire departments, and medical services), real-time telemetry and mission-related information cannot be shared as no common operational platform exists.

To address the above issues, Japan Aerospace Exploration Agency (JAXA) has been developing technologies for disaster relief (D-NET) in two main directions. First, to speed up data acquisition and reduce the errors during voice transmissions when assigning missions, JAXA developed a system for real-time data transmission. The system enables a real-time connection between the pilot of a disaster relief aircraft and a ground server (more details can be found in [1]). The D-NET system, being installed on fire department helicopters and used in nominal and off-nominal operations, has already proven to solve the problems of delayed and erroneous transmissions. Based on that foundation, the continued line of research in D-NET has been the development of an integrated aircraft operation system to support information acquisition, mission planning, and decision making by using and coordinating manned vehicles, unmanned vehicles, and satellites. The objectives in this area are to acquire data efficiently from available sources (e.g., satellites, helicopters, and unmanned aircraft systems) and to analyze these data in order to provide optimal resource allocation and flight trajectory plans for response vehicles, which can in turn be integrated and applied in actual rescue operations. D-NET functions are summarized in Fig. 1. The system has three main blocks: 1) data/information acquisition, 2) optimal planning, and 3) operation execution. D-NET makes use of the capabilities of each vehicle and optimizes the overall performance of the system by assigning missions according to the vehicle's equipage, state, and location. In terms of UAS applications, D-NET plans and assigns data acquisition missions to UAS in order to spare resources from the manned aircraft fleet so that more helicopters can be assigned to rescue missions. D-NET's strategic planning capabilities can efficiently assign missions and generate flight plans for large disaster areas (e.g., very wide-scale disaster exceeding 15,000 km^2) and multiple vehicles (e.g., 50 vehicles). More details on the optimization algorithm can be found in our past work [8].

So far, the focus of research on UAS applications in disaster response has been on single or small numbers of aircraft operations. Although the growth and advancement of UAS technologies in disaster response situations has increased, the use of UAS to support emergencies is still limited by the manual coordination that is needed to safely operate multiple aircraft in a common area. Currently, there is no existing system established to manage the coordination between multiple UAS operators and provide the situation awareness needed to safely operate together. Additionally, the coordination between manned and unmanned missions is only done during preflight preparations. The lack of coordination and situation awareness limits the use of UAS: the adaptability of changing UAS missions based on dynamic conditions degrades the level of safety as the number of UAS operations increases in a given area. Situation awareness is critical for aircraft operators as well as response managers in developing and maintaining an accurate assessment of the current deployment of assets and status of operations, which would aid in a more integrated and informed decision-making process. In 2015, NASA formally embarked on the development and maturation of a UAS Traffic Management (UTM) concept, including the technical development and testing of the associated communication, data, and information architecture. NASA's UTM technology was developed and tested with industry partners through a series of increasingly complex operational environments [9].

The objectives of UTM are to enable a safe and scalable approach to support the use of small UAS operations in low-altitude airspace, providing flexibility in use of the airspace where possible and structure where necessary. The integration of Public Safety entities and their operations into the UTM ecosystem has been a consistent focus area throughout the development and demonstrations. The UTM technology development and assessments have focused on the ability to provide common situation awareness for operators and stakeholders, strategic 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. However, the traditional focus with regard to air assets and disaster response has been on manned aircraft operations. As a result, there are certain challenges in the further integration of UAS with manned

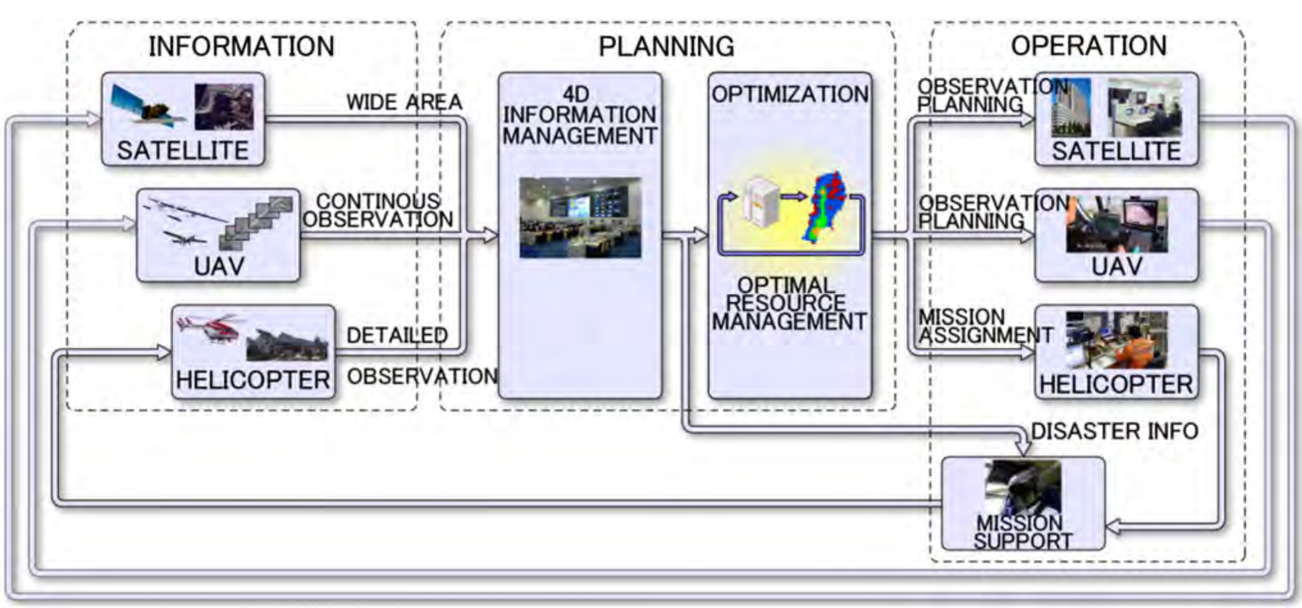

Fig. 1 D-NET functions.

Table 1 Complementary functions of D-NET and UTM systems

Function	D-NET	UTM
Preflight operation phase		
Aircraft mission assignment optimization	✓	
Aircraft route optimization	✓	
Strategic deconfliction: Operation Plan		✓
Strategic deconfliction: Mission Assignment	✓	
Operational intent sharing		✓
Data request (e.g., request for satellite imagery)	✓	
Priority operation handling		✓
In-flight operation phase		
In-flight mission monitoring	✓	✓
Onboard mission support (D-PAS)	✓	
Operational intent sharing		✓
Conformance monitoring		✓
Priority operation handling		✓

aircraft into the overall response that require further research. The capabilities of the D-NET and UTM systems have been recognized as highly complementary, as shown in Table 1. The integration of the two systems provides an avenue toward overcoming the challenges of effectively integrating manned and unmanned systems in disaster response situations.

B. Preflight (Flight-Planning) Phase Challenges

The technical challenges associated with UAS integration in disaster relief can be divided into preflight, in-flight, and postflight phases. This paper will focus primarily on technologies that address the preflight and in-flight challenges. However, the authors acknowledge that further research and development to support efficiencies in postflight operations (e.g., transferring data from UAS to operations command centers) is needed. In the following subsections, the challenges associated with each phase are posed with the solution implemented and tested to address the stated challenges.

During the preflight phase, the following challenges should be addressed:

1) Are missions optimally assigned considering available resources and disaster area?

In the immediate aftermath of a large-scale disaster, demand (search and rescue missions) exceeds available resources (manned and unmanned aircraft, ground vehicles, etc.), which makes vehicle assignment and route planning an optimization problem. Vehicle routing has been subject to multiple studies [10,11], but the scale of the problem and fleet heterogeneity pose a problem in real-world applications. There have been several approaches to model the reconnaissance problem. Assuming that the entire disaster area needs to be covered, the problem becomes equivalent to the search grid problem once the disaster area is broken down into cells of appropriate size to reflect the reconnaissance capabilities of each aircraft. There has been extensive research on vehicle path planning, in most cases robot path planning. Applied methods include genetic algorithms [12], Markov decision processes [13], ant colony algorithms [14], and neural networks [15], to name a few. When the area is discretized into grids in which centers are modeled as nodes, the problem can be referred to as the classic traveling salesman problem as well. In all of the above research papers, however, the size of the instances cannot reflect adequately the number of observation grids of the disaster area. For an aircraft to obtain sufficient view of the area, flying above a grid 1 km on each side or smaller is preferable. In the case of a large-scale disaster, where the system under development is likely to be applied, this would result in at least 10,000 cells/nodes. In D-NET's optimizer, the system first clusters the cells and then looks for the best route within each cluster. This particular challenge, however, will be addressed in a follow-on publication.

2) Are the planned missions free of conflicts in the airspace?

Disaster relief missions are often performed by vehicles belonging to different organizations, which do not necessarily coordinate their planning. D-NET centralized mission assignment and flight planning to solve this issue, but the option for UASs operated by different operators still needed to be considered. UTM was developed as means to coordinate and strategically deconflict operations from different operators in the airspace. To combine the strengths of the two systems, a connection was made through the development of D-NET/UTM translator software (DLinkUTM) that provided the ability to plan and verify real-time conflict-free operations of integrated manned and unmanned operations supported by D-NET and UTM.

3) When flight plans are not conflict-free, can the conflict be resolved by replanning?

Strategic deconfliction of the four-dimensional (4D) flight plan volumes can be done by either changing the flight plan geography or shifting the flight plan in time. UTM provided the necessary safety separation margins and operational information to D-NET for replanning as part of the preflight strategic deconfliction process.

C. In-Flight Phase Challenges

The in-flight phase poses the following challenges:

1) Is the UAS flying in conformance to its flight plan?

UAS real-time telemetry data are transmitted from D-NET to UTM via DLinkUTM. UTM checks conformance between the flight plan and actual flight, and it issues alerts as needed. For example, each position report is checked for its location within the geographic and temporal bounds of the operation's established Operation Volume(s). If the position report is near the boundary of the Operation Volume or the frequency of reports does not meet the minimum requirements set by UTM, the operation state transitions from an Active state to a Non-Conforming state with associated alerts to the operator. If the position is outside of the volumes or the lack of position reports continues, the operation transitions to a Rogue state, indicating a critical inability for the operation to remain predictable and within the planned airspace volumes.

2) Can the UAS transmit survey information (e.g., victim's location)?

A main advantage of UAS is the wide variety of payload and equipment they can carry onboard. In reconnaissance missions, information transmitted live from an onboard camera is used to evaluate the damages and identify victims' locations in real time. In this test, there was no camera onboard the UAS, so the second challenge was not tested. However, the state of the victim and disaster area information can be shared through D-NET [16,17].

3) Is the UAS aware of other traffic (manned and unmanned) in the airspace and, if necessary, can the UAS modify its flight plan to avoid conflict?

Nominal UAS operations will, in general, follow a flight plan developed and agreed with operators and relevant players before the flight. In the case of disaster relief, however, flights of both manned and unmanned vehicles will often differ from the original flight plans due to the dynamic nature of missions (search and rescue, for example). Therefore, flight plan modification capability is necessary. In this test, manned aircraft (JAXA's experimental helicopter) flight plan and position data were submitted to UTM and the vehicle was treated as a priority user. Alerts were issued to UAS in the area of airspace that the priority manned aircraft was scheduled to operate in, which provided the opportunity for the UAS operators to perform plan modifications through UTM to allow the vehicle to safely return to base.

III. D-NET/UTM Integration

The integrated system between JAXA's D-NET and NASA's UTM is focused on the safe and efficient use of UASs in immediate postdisaster relief operations. The integrated operations are described in two stages corresponding to the technical challenge stages (preflight and in-flight) discussed in Sec. II. Mission assignments and planning are done in D-NET; thus all mission trajectories are generated within D-NET as well. Each UAS flight plan is essentially a trajectory, made of multiple line segments, each defined by the 4D coordinates of its edges. Based on the received mission trajectories, UTM checks that safety constraints are met and provides operational volumes back to D-NET. The operational volumes represent a buffer around the mission trajectory to help safely separate it from other operations. These operational volumes are used to strategically deconflict with other operations before departure and are also used to monitor conformance of the aircraft during the flight. D-NET visualization tools used by the command centers and UAS operators were modified to include the operational volumes received from UTM. Note that UTM's operational volume generation logic is not communicated to D-NET, nor is the logic according to which missions are generated in D-NET conveyed to UTM. Both systems treat each other as black boxes, which makes the entire integration concept flexible to variations and valid even when either of the systems updates its internal algorithms.

However, helicopter operations are conducted under visual flight rules (VFRs), which often results in large deviations from the original flight plan that the pilots use only as a reference. Although UTM has been designed to support operations from rural to urban environments, much of the more recent focus has been on situations and use cases in which greater precision and control is expected of operators with more efficient use of the airspace. As a result, the operational volumes often observed are based on line-segmented flight plans that require more precise waypoint following capabilities, which were found to be too prescriptive for VFR operations such as those supporting disaster relief. To account for the large variability in flight paths based on visual cues observed from VFR disaster relief operations, the operation plans and associated volumes in UTM were given large buffers during the preflight planning for manned aircraft operating under VFR. To promote efficient use of the airspace, future research will explore more tactical and dynamic operation plan definitions with real-time modifications for manned VFR operations to reduce the conservative buffers needed in preflight planning.

The D-NET/UTM integration approach taken as part of this effort leveraged and adapted the existing capabilities of both systems. Therefore, helicopter VFR flights plans were submitted to UTM not as line segments, but as relatively large operational volumes to account for flight path variability. Additionally, current disaster relief practices prioritize manned over unmanned aircraft operations. In other words, even if there is an accepted or active UAS operation in a common area of airspace, the helicopter's mission needs to be given priority and have that prioritization communicated to others. To accurately model such practices, the helicopter's operation plan within UTM is assigned a priority status and its operation plan is prioritized over other UTM operations. During preflight planning or during an operation, if a priority user has an operation plan that conflicts with a planned or existing operation of lower priority, then the lower priority mission will be notified to modify their plans to resolve the conflict. UTM facilitates the verification of conflict-free operation plans and the notification of conflicts to all affected parties as part of its strategic deconfliction functionality. Operators with lower priority who plan missions that conflict with a priority user will be notified that UTM cannot accept their operation when the conflict exists with the priority user. The conceptual interaction between D-NET and UTM in the preflight stage is shown in the left panel of Fig. 2.

During the in-flight stage (Fig. 2, right panel), D-NET receives UAS and helicopter tracking data and converts the data for transmission to UTM in the appropriate format. As described previously, UTM uses aircraft positions to check the aircraft conformance relative to the operation volume(s) and issue alerts accordingly if the aircraft starts to deviate from the prescribed operation volume. Since operation volumes are deconflicted predeparture, safe separation is maintained if aircraft remain within their intended operation volumes. Notifications of nonconformance to operation volumes are shared with the operator in violation as well as the operations in nearby proximity for situation awareness. Performing strategic deconfliction in planning and monitoring conformance during the in-flight stages contributes to safe mission execution and provides much needed situation awareness for operators and response managers. UAS information (operational volumes and current position) is sent to the helicopter as well via a newly developed function of the already existing D-NET onboard mission support system [17]. Further details on the initial architecture and overall concept of operations exploration can be found in [3].

To advance the concept and address the challenges presented in Sec. II, an interface was developed between the D-NET and UTM systems, and data were exchanged between the two systems in real time. Although D-NET and UTM can both serve as portable systems, they were developed independently and not initially designed to exchange information with each other. To address this issue and enable integrated support for disaster relief in real time, translator software referred to as DLinkUTM was designed and developed to enable the exchange of information. Figure 3 presents the architecture and information flow of the integrated D-NET/UTM system. All information exchanges between D-NET and UTM were established through DLinkUTM, which maintains concurrent connections to D-NET servers and UTM. The UTM system was hosted from servers at NASA Ames Research Center in California, whereas the D-NET system was hosted from the JAXA servers in Japan. The interface also provides information on the vehicle's ID (e.g., UAV1, UAV2, etc.), the UTM state of the operation (ACCEPTED for a flight plan been accepted by UTM, REJECTED, CANCELLED, etc.), the Globally Unique Flight Identifier (GUFI), and flight plan number for each vehicle.

D-NET/UTM integration required that UAS operational volumes be visible onboard the helicopter in real time. This was achieved by adding such functionality to the existing onboard D-NET mission support technology. D-NET's mission support tool is a fully portable system, consisting of a satellite transmission component, a digital antenna, and a touch-screen display which enables manual input on behalf of the operator onboard the helicopter (see Fig. 4). The touch-screen display allows the crew not only to confirm the position of other D-NET equipped manned aircraft in real time, but also to input

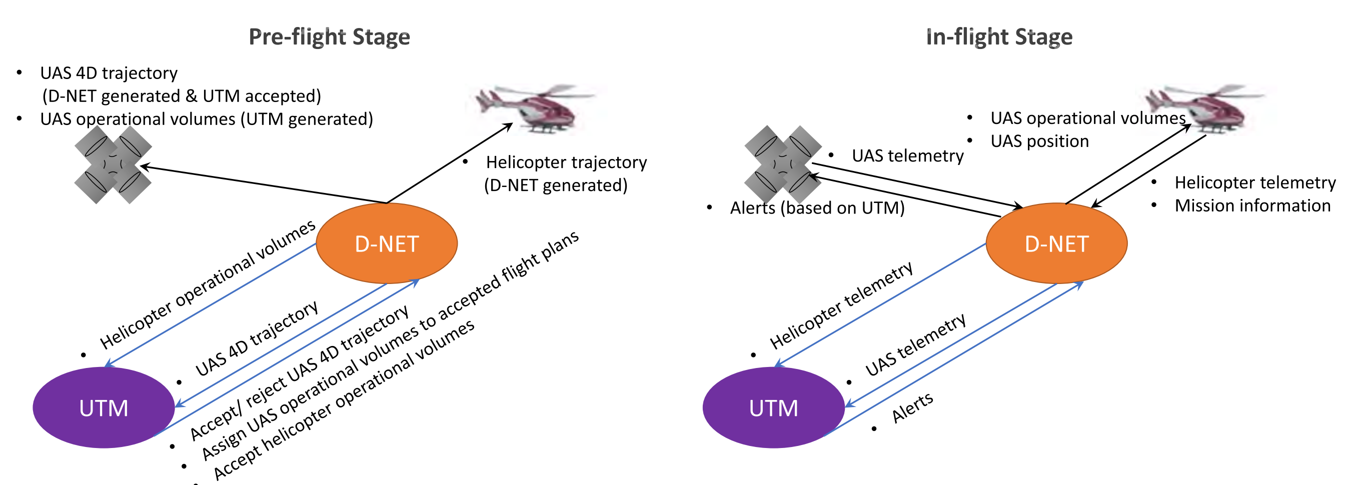

Fig. 2 D-NET/UTM conceptual interaction.

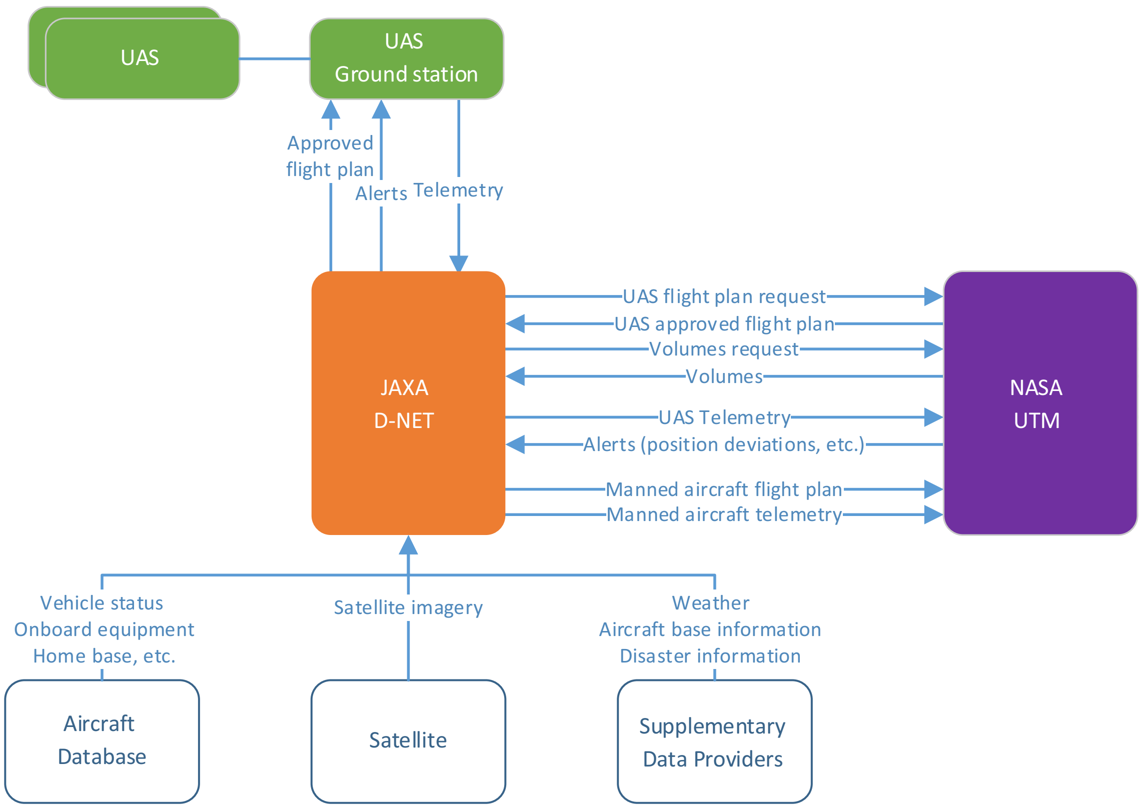

Fig. 3 D-NET/UTM interface architecture.

Fig. 4 D-NET fully portable onboard mission support system.

data, such as disaster type or evacuee information, and send it to the ground support system. The interface has been developed considering pilot, doctor, and fire department personnel's feedback to assure usability and high efficiency.

IV. Test Scenario

To test the integration of D-NET and UTM in a realistic and applied context, the following test scenario was developed. Following a major disaster event, UASs supported by UTM were assigned by D-NET to search the disaster area for evacuees. While performing the search and rescue operation, the UAS identifies a person in distress who is in need of assistance. The D-NET implementation on the UAS allows the identified person's whereabouts to be communicated to the command center where a manned helicopter is assigned to perform the rescue and extraction of the person in distress. The intended operation plan of the helicopter is communicated through UTM as a priority operation. In its response, the rescue helicopter enters the airspace where UAS are conducting ongoing operations. This causes a conflict in the intended operation of the rescue helicopter and the ongoing UAS operations in the area, which results in notifications through UTM to the UAS operators to deconflict their operation from the priority rescue helicopter. Through this communication, the helicopter is able to transverse the airspace without delay due to the other UAS giving them the "right of way," thus allowing quick extraction and transport of the person to a safe location. As part of this process, the UAS operations are made aware of the potential conflict and are able to replan their mission to ensure that their objectives are met without disrupting the high-priority rescue operation. In contrast to nominal operations, disaster response is very likely to have a manned aircraft (most often a medevac or rescue helicopter) enter low-altitude airspace that is approved for UAS operations. For all vehicles to operate safely, mission prioritization, planning, and execution become crucial. The scenario developed for this flight test provided the opportunity to test the capabilities of both systems (D-NET and UTM) with respect to these challenges.

V. Flight Test

The primary goal of the flight test was to demonstrate that the integration of D-NET and UTM can enable the safe and efficient use of airspace by both manned and unmanned aircraft. The underlying objectives defined to achieve that goal were to connect the two remote systems (D-NET and UTM) in real time, prove out the validity of the mobility of the concept through remote system connections, provide real-time visualizations of flight and operations data for operator and command situation awareness, and demonstrate the benefit and applicability of UTM to the incorporation of UAS in disaster response efforts through data exchanges between D-NET and aircraft operators. To address these objectives, the scenario described in Sec. IV was formulated along with an associated flight test plan, shown in Fig. 5, which was successfully executed through the interaction between connected systems and operators as part of the large-scale Ehime Prefecture Disaster Drill conducted in 2018 [18].

The Ehime Prefecture in Japan has shown interest in using UAS for aerial observation of evacuation routes in the case of a disaster, specifically in the vicinity of the Ikata nuclear power plant. The large-scale disaster drill conducted on October 12, 2018, and coordinated by the Ehime Prefectural Government included 77 organizations and more than 7000 participants. The event focused on reconnaissance and evacuation procedures in the event of a nuclear power plant accident. D-NET's flight test represented a single mission in the broader large-scale disaster drill and was composed

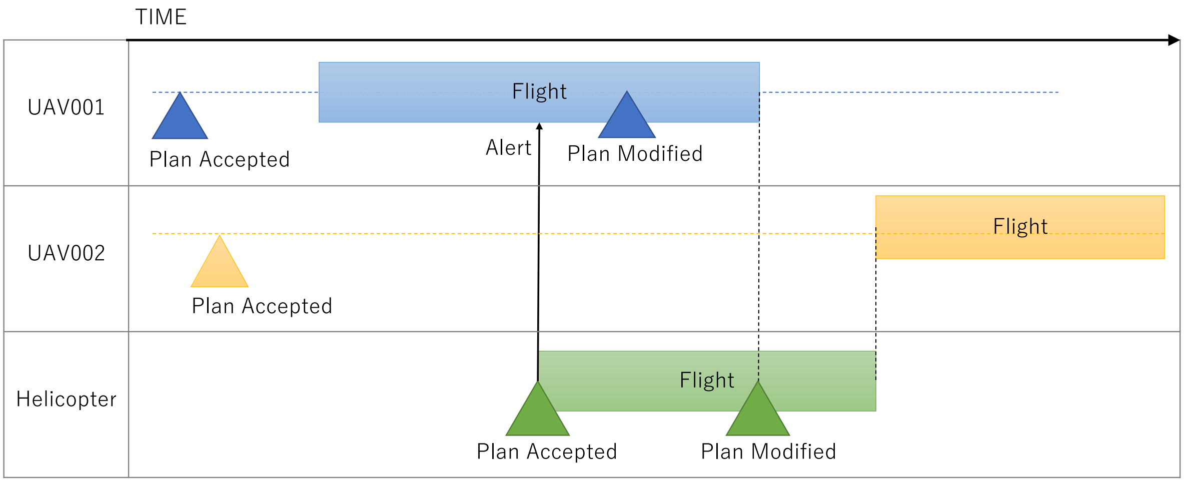

Fig. 5 Flight test operation timeline.

of a UAS flight crew located at a UAS test site near the city of Yawatahama, a mission support team in the command center in Matsuyama where the command center headquarters were located, and a helicopter flight crew dispatching from the Matsuyama Airport. Multiple flights were planned throughout the day involving a helicopter to dispatch from Matsuyama airport and fly southwest along the coastline and through the UAS test range near Yawatahama. The scenario, as described in Sec. IV, initiated interactions between the operations of the manned and unmanned aircraft at the Yawatahama UAS test location. The UAS used in the flight test was an enRoute QC730 quadrotor [19]. However, due to strong gusting winds sustained above 10 m/s at the Yawatahama test site, the UAS was unable to safely operate on the day of the disaster drill. High winds can produce instability for small UAS platforms that may result in unplanned landing which can cause risk to humans and property. The high winds had no impact on the helicopter operations. Because of the high winds, the UAS operations were simulated using the software in the loop (SITL) flight simulator that is part of the Mission Planner ground control station. These simulated operations used the same flight paths as the physical aircraft and model the expected vehicle behavior of the UAS. Furthermore, the simulated UAS still produced the expected interactions between the UAS and manned aircraft. Given that the high gusting winds would have significantly impacted the UAS flight performance but had minimal impact on the helicopter performance, the results of using the simulated UAS more closely represented an operation under a minimal wind condition. The manned aircraft was JAXA's experimental helicopter BK117 C-2 [20]. It can carry up to eight people (two crew and six passengers), but in this flight test, three personnel were onboard the aircraft: two flight crew and one researcher. The helicopter was able to fly, and its flight plans and positioning data were successfully transmitted to UTM via D-NET. As part of the qualitative data collection, questionnaires and interviews were conducted with the disaster relief personnel, UAS pilots, and helicopter pilots to provide insight on the usability of the technology to support disaster response operations. On the day of the disaster drill, two series of flight tests were conducted: one in the morning and one in the afternoon. The flight tests were followed by crew debriefs and questionnaires to capture qualitative data. Both flight series followed the same scenario and flight plan as shown in Fig. 5. Three vehicles performing one flight each were involved in the D-NET/UTM integration. For each flight, a plan was submitted from D-NET to UTM (see Fig. 6) during the preflight phase. The UAS operator created their flight plan through D-NET, which was then submitted to UTM to check against known airspace constraints (e.g., conflicting operations, flight restrictions, etc.). UTM reported a rejection of submitted operation plans if conflicts in the form of overlapping operation volumes (in time and space) were found between the proposed flight and other operators' existing plans or known airspace constraints. When the submitted plan did not conflict geographically and temporally with any previously submitted operations, it was approved and transitioned to an ACCEPTED state. However, if a conflict was detected, the plan acceptance depended on the priority of the planned operation. Under this flight scenario, the manned aircraft was treated as a priority vehicle, so even though its flight plan was in conflict with the flight operation of the first unmanned aircraft already airborne, the helicopter's flight plan was accepted and an alert was issued to the unmanned vehicle to clear the airspace. Therefore, the flight test allowed for verification of each of the flight plan acceptance scenario, alert generation, and flight plan modification. The flight test site and operational areas of the UAS and the manned aircraft are shown in Fig. 7.

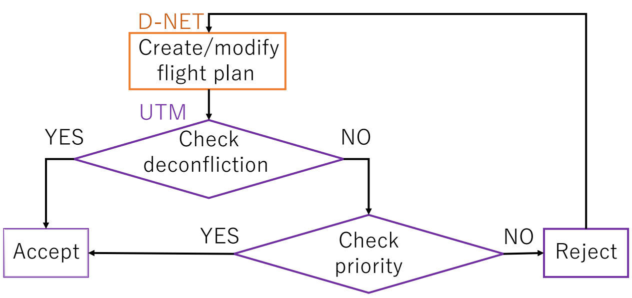

Fig. 6 Flight plan acceptance flow.

Fig. 7 Flight test site and operational areas.

A. Test Setup

In support of the flight test, several teams of personnel across multiple locations were involved in supporting different aspects of the operation. In Japan, two teams were on station: one team was located at the disaster drill's dedicated Operations Center in Matsuyama City, Ehime Prefecture, and another team located at a UAS test site along the peninsula near Yawatahama. The team at the Operations Center consisted of JAXA and NASA researchers along with technical staff that monitored the simulated disaster situation occurring across the disaster drill and interfaced with the D-NET and UTM systems. Information exchanges with the respective systems were managed from the Operations Center, and operational situation awareness was maintained through monitoring data in real time via various interfaces (Fig. 8). The research team located along the peninsula near Yawatahama included JAXA and NASA researchers accompanied by a UAS flight crew and UAS aircraft. The role of the research team and flight crew at the UAS test site was to conduct live UAS flight operations in support of a coordinated disaster response effort (Fig. 9). A third research team was located at NASA Ames Research Center in California within the Airspace Operations Laboratory (Fig. 10). This research team consisted of NASA researchers, engineers, and systems administrators who monitored the test remotely through visualizations of the UTM data exchanges as well as coordinated communications with the teams in Japan. Position updates of operations, operational state, and their management within the UTM system were shown in real time on multiple displays, as shown in Fig. 8. The health of the UTM system, data collection, weather in Japan, and system connectivity were also monitored from the Airspace Operations Laboratory during the test to ensure continuous connectivity and proper functioning of the UTM system. There was also the helicopter crew that performed the live manned flight and enabled the interaction with UAS supported through UTM.

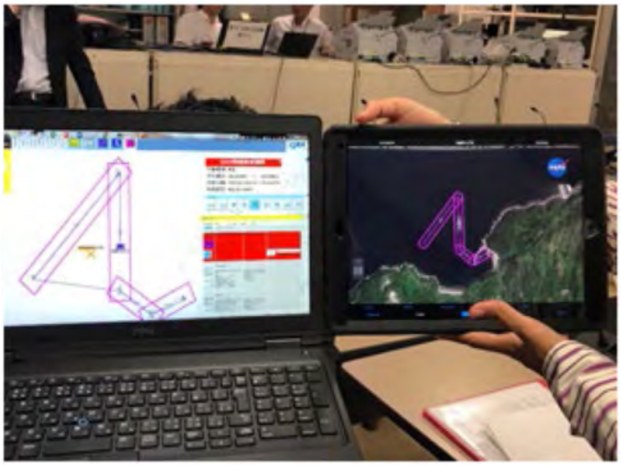

Fig. 8 D-NET and UTM interfaces used by researchers in the Operations Center.

Fig. 9 Crewmember of the flight team at the UAS site.

B. Preflight (Flight-Planning) Phase

At the beginning of the test, D-NET was connected to NASA's UAS Service Supplier (USS) through DLinkUTM. D-NET provided flight plans consisting of 4D line segments to UTM through DLinkUTM. Each segment of a flight plan was defined by a lateral component consisting of two waypoints' lateral coordinates, minimum and maximum altitude (0 and 492 ft, respectively, for all segments) allowed for the flight, and beginning and end times for each segment. The time allocated to each segment was calculated assuming a ground speed of approximately 6 kt and adding a buffer of 10 min to reflect the uncertainties of live operations. Each flight plan was associated with a unique identifier that was used to correlate position information, flight plans, operation state, and messaging to a specific operation. During the flight test, the flight plan associated with an operator with the callsign UAV1 was sent to UTM, which confirmed that there were no conflicting flights in the same airspace and sent an ACCEPTED message with associated operational volumes (safety separation buffer around the flight plan) for each flight segment. A globally unique flight identifier (GUFI) was assigned to the first operation of UAV1 by UTM to correlate all state data with this operation. The lateral trajectory planned for UAV1 is depicted in Fig. 11. This operation consisted of five waypoints defining seven operational flight segments. Note that the geographies of segment 1 (connecting waypoints 1 and 2) and segment 2 (connecting waypoints 2 and 3) are the same as those of segment 6 and 7, but the flight direction is different. D-NET submitted a flight plan defined by line

Fig. 10 Airspace Operations Laboratory at NASA Ames Research Center.

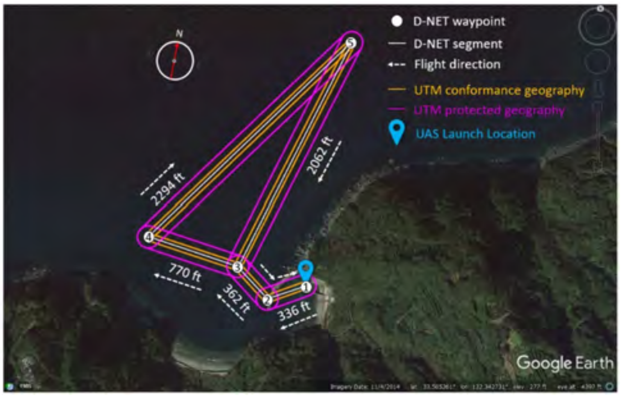

Fig. 11 UAV1 original flight plan and operation volumes.

segments (shown in white) and UTM applied additional buffers (shown in magenta and orange) to the submitted geographies to account for potential uncertainties. Shortly after the acceptance of UAV1's operation, a flight plan was submitted by another operator with the callsign UAV2. The UAV2 operator's flight plan was submitted to UTM via DLinkUTM but partially overlapped with the accepted operation from UAV1 and therefore was rejected due to the conflict. To address the conflict, the flight plan for the UAV2 operation was manually deconflicted by shifting the start and end time of the operation. For the experiment, the time shifting was done manually but later D-NET capabilities not tested in this flight test include automatic preplanning using spatial and temporal modification to support deconfliction. Following the manual time shift, the UAV2 operator's newly generated flight plan was then submitted to UTM and accepted. The flight plan submission, deconfliction, and acceptance addressed the preflight challenges discussed in Sec. II. Typically, the coordination to deconflict operations occurs at the beginning of a day of the operation and is static throughout the day unless changes are needed, which often require lengthy manual radio communication. Using UTM and D-NET cut the coordination times between operators and dispatch to seconds (it took only 42 s for the modified plan of UAV2 to be accepted) and enabled more rapid on-demand changes to operations planning. Once the flight plan of UAV2 was accepted, the dispatchers at the operation centers knew what time the search over the target areas would be completed, thus allowing them to plan accordingly for other missions. Furthermore, the time between flight time submission and UTM's response showed that both systems can communicate in real time with minimum delay.

C. In-Flight Phase

In accordance to its flight plan accepted by UTM, UAV1 could take off no earlier than 09:10:00 JST and complete the first leg of the mission between waypoint 1 and waypoint 2 no later than 09:20:33 JST. Once preflight preparation was complete and the operator was ready for takeoff, they issued an "ALL CLEAR" message through D-NET to UTM to set the operation into an activated state. To emulate the expected spatial distribution of UAS operators during a disaster response event, the UAS Ground control stations were in two different locations during the disaster event using D-NET over cellular connection. As weather conditions during the disaster drill restricted the flight of the UAS, the ground control stations were used to simulate the UAS aircraft operations. In addition to UTM providing strategic deconfliction during the preflight phase, position information from live and simulated aircraft were also provided to UTM during the in-flight phase to monitor conformance to the operation plan buffers around the flight plan. In instances where an aircraft deviates outside the operation plan, UTM will issue an alert to the aircraft operator in violation and will also issue a notification to other operators in the proximity for awareness of potential conflicts with a nonconforming operation. Once the UAV1 operation state became ACTIVE, position information was sent via DLinkUTM at 1 s intervals to UTM for conformance monitoring. D-NET and UTM user interfaces depicted information on moving maps containing multiple operations with different UAS operators that was available to the Operations Center engineers in Ehime and researchers in the Airspace Operations Laboratory facility in California. Both systems could successfully communicate with one another despite their different geographic locations. The accessibility of operation information is extremely beneficial in disaster response events where Operations Centers, dispatch, manned operations, and unmanned operations often are not centrally located. Information can be distributed in real time and available to those who need it to plan operations and response actions based on the timely information. Furthermore, the accessibility of operation data also allows for more adaptive responses to ever-changing conditions due to the disaster, which supports more efficient management of resources.

According to the scenario, UAV1 discovered a person in need of rescue and relayed that information to D-NET. The victim's location was then communicated to the manned aircraft, JAXA's experimental helicopter JA21RH, to plan an extraction operation. Through a D-NET relay, the UAV operational volume information was available to the onboard mission support system and shown to the helicopter flight crew, as seen in Fig. 12. The helicopter flight crew was therefore aware of the UAV operation plan. This contributed to the pilot's situation awareness with respect to potential impacts on the operation.

Using the D-NET onboard mission support system, a request was issued by the helicopter flight crew at 09:15:56 JST to the UAV1 crew to clear the airspace. To facilitate this request, existing capabilities in UTM were adapted to consider a manned aircraft as a priority user. This status allowed for the operation plans issued for the manned aircraft to have priority over all other UAV operators with conflicting operations. Typically, manned helicopter operations are conducted under visual flight rules (VFR) often using visual reference to guide their flight. However, for the purposes of this flight test, operational 4D volumes analogous to those used by the UAV operators were submitted to UTM. Given the intended helicopter flight path, operation volumes were defined with large buffers to account for expected deviations due to expected behavior of flight crews following visual references. The volumes submitted only covered the portion of JA21RH's flight in the proximity of the UAV's area, but a later flight included operation volumes that covered the entirety of the helicopter's flight path to the rescue site. JA21RH departed from Matsuyama Airport located approximately 50 km away from the UAV flight zone. JA21RH provided position information to UTM via D-NET and was in an ACTIVE state as it entered the operation volumes about 10 km away from the UAV flight zone. Meanwhile, the helicopter operation was monitored for conformance with real-time status available for situation awareness at the Operations Center and for other nearby operators. JA21RH's operational volumes overlapped with the operation volume of UAV1 that was already accepted by UTM. The UTM system implemented a first-come, first-served policy to manage airspace use for commercial UAS operators that typically have equitable rights to airspace access. However, as stated previously, the prioritization of operations exists in disaster response situations and is an important aspect to maintain as new systems and concepts are introduced. For the scenario, evacuating a victim using a helicopter holds

Fig. 12 Onboard D-NET portable system view. UAV area is shown in yellow, and the present helicopter position is shown by the red arrow.

priority to other surveillance or reconnaissance UAS operations. Therefore, the helicopter flight plan Flight plan 003001_1 was sent from D-NET to UTM as a priority user and was accepted by UTM regardless of conflicting operation (Helicopter: Plan Accepted in Fig. 5). The telemetry of the helicopter, which was transmitted through D-NET's onboard mission support to D-NET on the ground, was then relayed to UTM. Position reports from the helicopter to D-NET were available every 20 s since the transmission is established through satellite connection. Faster position reporting frequencies were technically possible, but, due to prohibitive costs, it was determined that 20 s updates were sufficient for the purposes of this test. Given that position reports are typically expected at higher frequencies within UTM, the DLinkUTM used a zero-order hold to maintain the most recent position report at the expected UTM frequency until an update was received from the helicopter. Upon receiving the flight plan of the priority user JA21RH, UTM issued an alert through D-NET to the UAV1 operator to notify them that the UAV1 operation must clear the airspace due to a priority operation (Fig. 13 left panel). D-NET then created a new flight plan for the UAV1 to return to base. The modified flight plan included only the current segment and the future segments necessary for the return flight. Given that UAV1 was currently aloft, the operation plan modification considered the aircraft's current flight segment between waypoint 3 and waypoint 4 when building the return to base revised operation. After it was determined by UTM that no conflict existed with the priority operation, the revised operation was accepted and the vehicle could then initiate a safe return to base (Fig. 13 [right panel] and Fig. 14). After the simulated UAV landed, the UAV operators notified the Operations Center via the cellular network that the UAV had safely touched down. To indicate that the operation was complete, the DLinkUTM sent a CLOSED message to UTM, which indicated to all stakeholders that the operation was closed. Once the airspace was clear of potential conflicts with UAVs, the area of airspace needed to accommodate the JA21RH operation volumes, including the airspace previously assigned to UAV1, was available for the helicopter to complete its rescue mission of the victim. The flight tests at the disaster drill did not include an actual landing of the helicopter as the experiment was primarily focused on airspace interaction between the manned and unmanned operations; so the helicopter conducted an overflight of the UAV airspace on its way to a simulated landing and subsequent return to base. Once JA21RH left the UAV airspace and concluded its operation, the mission was closed and the airspace was available for use by other operations. The original scenario included testing of the simulated UAV2 as well. However, because UAV1 flights were substituted by simulations due to bad weather, the UAV2 simulations were not conducted.

VI. Flight Test Results and Analysis

The detailed scenario that was developed allowed for multiple D-NET and UTM capabilities to be tested in a realistic disaster recovery environment. The flight test primarily looked at the interactions between the UAS operator, helicopter operator, and the D-NET and UTM systems. The test was intended to inform how

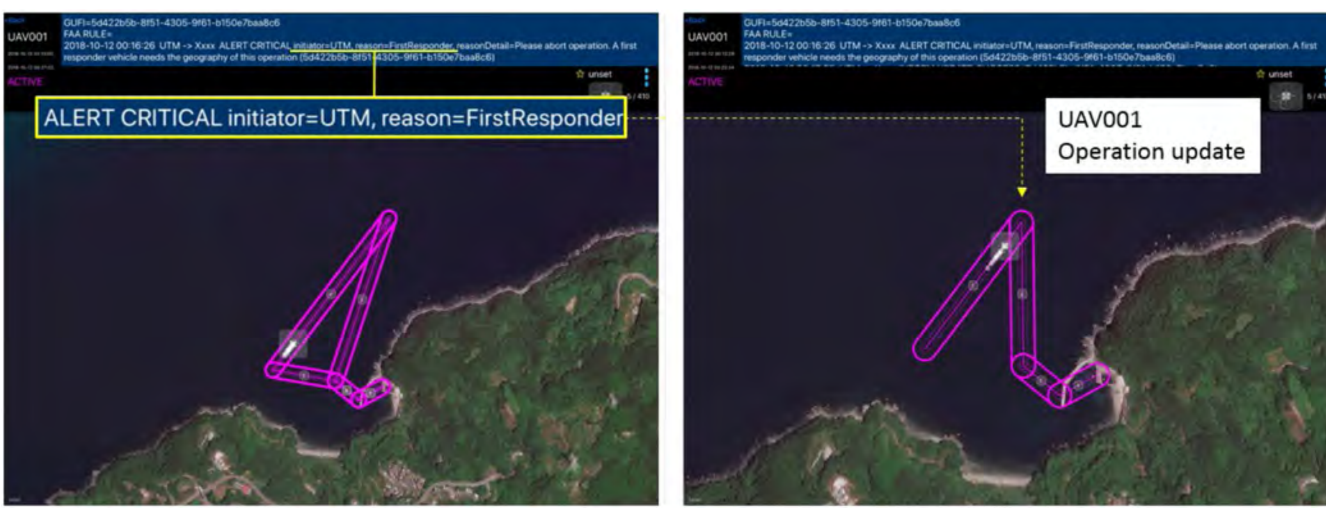

Fig. 13 UAV1 was sent an alert informing of priority user in the same airspace.

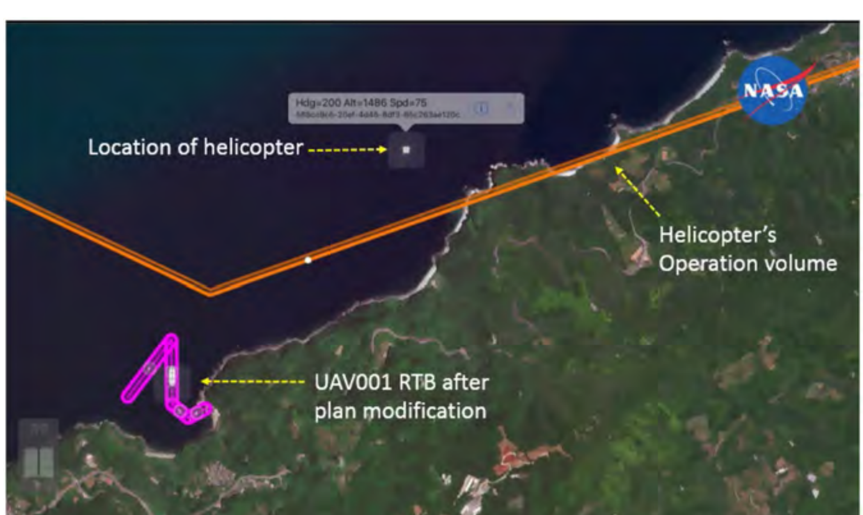

Fig. 14 Helicopter's operational volume, location, and UAV1 modified flight plan.

Table 2 Number of information exchanges throughout preparation and testing

Information exchange	Count
Operations	117
UTM messages	363
Positions	5364

Table 3 Message types and counts observed across preparation and testing

Message category	Count
INFORM	203
INTENT	81
ALERT	79

UAS can be integrated safely into the disaster response aircraft operation workflow using mission planning and airspace management automation technologies. It was evident that before aircraft departure, the timeliness of sharing information was a clear improvement upon existing workflows. The raised awareness of existing and planned operations allowed UAV operators, helicopter operators, and the Operations Center to have visibility into the intent of other missions, and when these missions are expected to start and end to facilitate more efficient strategic planning. The test illustrated that when communication means were available, such as the cellular network, the operational data of others were useful in supporting deconfliction with planned and existing operations. Future work should focus on degraded or intermittent communication over the cellular network, and alternative means of communications in the event the cellular network is not available. Establishing prioritization using type of vehicles (manned or unmanned) was effective in providing notification of the need for priority airspace use in the testing environment. However, different operations (manned or unmanned) may have different priorities at different times. Future work should explore establishing levels of priority in a disaster response operation, using mission planning tools such as D-NET to specify prioritization, and codifying the “right of way” rules according to levels of priority in UTM. Establishing these rules would also need to address how operators should facilitate negotiation of airspace use in the event that two or more operations are in conflict at the same priority level.

During the in-flight phase, communication between D-NET and UTM was effective in providing sufficient and timely information exchange for disaster recovery support. As shown in Table 2, throughout preparation and testing, 117 operations were submitted from D-NET to UTM. A total of 363 messages were exchanged between both systems through DLinkUTM. The number of positions reports submitted was 5364, as most operation exchanges were meant to test flight planning capabilities and thus did not include position reports. Therefore, there was a high number of canceled operations, as seen in Fig. 15. The data that were exchanged between systems were expected given the interactions that were occurring during the scenario. In particular, all expected messages were received from the UTM system, relayed appropriately through DLinkUTM to the D-NET system, and displayed to the aircraft operators. Flight planning is crucial for efficient disaster relief, and this collaborative test demonstrated that UTM and D-NET can be used for both strategic and tactical planning. The immediate response from UTM, the ability to replan operations using D-NET, and a common operating picture shared by all the relevant users enabled a more adaptive response to changes occurring due to an evolving disaster response. Throughout preparation and testing, 79 alerts were sent to D-NET (Table 3). These alerts contributed to safe mission execution and proved that both systems are complementary. Future work should focus on the optimization of replanning operations and evaluating the impact of asynchronous information exchange and the time delay due to increased density of operations.

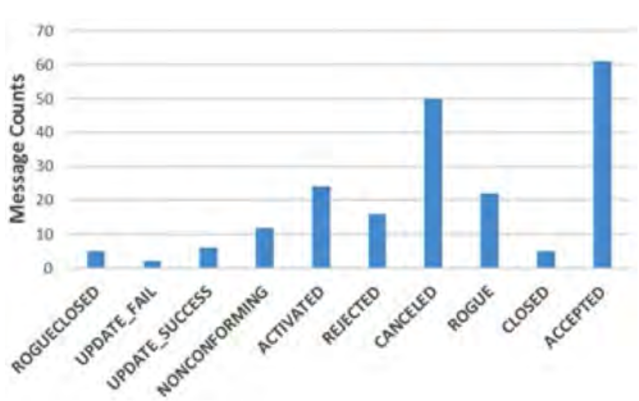

Fig. 15 Operation statistics (preparation and testing).

In addition to evaluation of the effectiveness of the data information exchange, feedback from pilots and disaster relief personnel was also obtained to gain qualitative insight into the usability of the technology to support disaster response. Feedback from the helicopter test pilot, who has over 22 years of disaster response experience, supported the concept of operation volumes assigned to manned VFR flights. It was indicated that a typical disaster response pilot would spend about 80% of the flight time looking out of the cockpit window, so it would be impractical to constantly look at the assigned volume(s) on a display. The display of operational volumes on a supplementary screen such as D-NET’s mission support system or on a set of paper instructions that might require significant head-down time could be a potential limitation to the implementation of this technology. However, the pilot indicated that they have sufficient awareness of their position during operations. So, in most cases, occasional checks of their relative position with respect to their assigned volume would be sufficient. The pilot’s recommendation was to incorporate heuristic landmarks (e.g., rivers, highways, railways), rather than arbitrary latitude/longitude polygons, in the processes of establishing manned aircraft operation volumes. Future work is needed to assess more automated replanning and human factors assessments around how information can be provided to a pilot in an effective way that does not distract from their existing tasks and provide information in intuitive ways corresponding to geographic references rather than flight paths.

With respect to UAS flying in adjacent airspace, the pilots said that they prefer to be alerted to the presence of UAS at distances within 3–5 km (3–5 min) before a predicted conflict. These distances would allow for approximately 5 min of lead time that would assure that the pilot has sufficient time to plan his/her actions in case a conflict occurs. Regardless of UAS behavior, the pilot will take actions to avoid encounter no later than 1 min before the predicted collision. Assuming that the pilot can look at D-NET’s mission support tool onboard, he/she will use D-NET/UTM information along with visual confirmation to identify the position of the UAS. The pilots reported that during all disaster response mission stages (preflight and during flight), they would need information on planned and active UAS missions. In flight, in particular, knowing UAS location and mission type would further aid their awareness and decision making. In disaster response, knowing the UAS mission type helps the helicopter pilot predict the UAS intended mission and expected behavior. A disaster relief pilot is likely to be sufficiently trained in order to leverage the skills needed to be reactive in changing environments, and the information provided from D-NET/UTM would aid his/her ability to assess the current operational state and predict the level of risk at a future state. It is well understood that given their size, UAS are often difficult to visually acquire from a cockpit. Therefore, even if a pilot was aware of a UAS in the vicinity, the search for the UAS would still take away from the existing tasks of the mission. The D-NET/UTM tools can help a pilot reduce the search time necessary for locating the UAS given the operation information provided through the D-NET/UTM technology.

VII. Conclusions

The flight tests conducted at the 2018 Ehime Prefecture disaster drill successfully demonstrated the application of UAVs to disaster response and showed that they can safely cooperate with manned aircraft to improve response efficiency. Connecting two remote systems (D-NET and UTM) in real time validated the mobility of the concept. The benefit and applicability of UTM to the incorporation of UAV in disaster response efforts was also shown through data exchanges with D-NET and operators. Additionally, the integration of UTM enabled informed planning for safe operations and facilitated situation awareness, which are critical elements in disaster response environments. It was the first time to have a manned aircraft as a planned operation in UTM, a demonstration of concept and technology that went very successfully. The disaster drill flight tests also exposed some of the challenges for D-NET and UTM in disaster response applications. Finally, gaining an understanding of the ways in which operators would use the information from both manned and unmanned aircraft in such situations provided very valuable feedback for future development.

References

[1] Okuno, Y., Kobayashi, K., and Ishii, H., "Development of a Helicopter Operations Management System for Disaster Relief Missions," *Journal of the American Helicopter Society*, Vol. 61, No. 1, 2016, pp. 1–9. https://doi.org/10.4050/JAHS.61.012006

[2] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J. E., III, "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," *AIAA Aviation, Technology, Integration and Operations Conference*, AIAA Paper 2016-3292, 2016. https://doi.org/10.2514/6.2016-3292

[3] Homola, J., Johnson, M., Kopardekar, P., Andreeva-Mori, A., Kubo, D., Kobayashi, K., and Okuno, Y., "UTM and D-NET: NASA and JAXA's Collaborative Research on Integrating Small UAS with Disaster Response Efforts," *AIAA Aviation Technology, Integration, and Operations Conference*, AIAA Paper 2018-3987, 2018. https://doi.org/10.2514/6.2018-3987

[4] "Use of Small Unmanned Aerial Systems for Emergency Management of Flooding," U.S. Department of Transportation Federal Highway Administration, 2019, https://www.fhwa.dot.gov/uas/resources/hif19019.pdf [retrieved 3 March 2020].

[5] Murphy, R., "Drones Save Lives in Disasters, When They're Allowed to Fly (Op-Ed)," Sept. 2015, https://www.space.com/30555-beginning-with-katrina-drones-save-lives-in-disasters.html [retrieved 1 Sept. 2020].

[6] "Three Things Japan Ground Self-Defence Force Expect from Disaster Relief Drones (in Japanese)," Fuji News Network (FNN), Sept. 2018, https://www.fnn.jp/posts/00362790HDK [retrieved 3 March 2020].

[7] "Nasu Avalanche Accident: Drones Used on Site (in Japanese)," Mainichi Shinbun, March 2018, https://mainichi.jp/articles/20180330/k00/00m/040/063000c [retrieved 3 March 2020].

[8] Andreeva-Mori, A., Kobayashi, K., Shindo, M., and Okuno, Y., "Optimal Aircraft Assignment in Immediate Post-Disaster Reconnaissance," *7th Asia-Pacific International Symposium on Aerospace Technology (APISAT)*, RAeS Australian Division and Engineers Australia, 2015.

[9] "UTM Concept of Operations," Federal Aviation Administration, https://www.faa.gov/uas/research_development/traffic_management/media/UTM_ConOps_v2.pdf [retrieved 11 Oct. 2020].

[10] Hsueh, C. F., Chen, H. K., and Chou, H. W., "Dynamic Vehicle Routing for Relief Logistics in Natural Disasters," *Vehicle Routing Problem*, edited by T. Caric, and H. Gold, I-Tech, Vienna, 2008, pp. 73–84. https://doi.org/10.5772/5641

[11] Ozdramar, L., and Demir, O., "A Hierarchical Clustering and Routing Procedure for Large Scale Disaster Relief Logistics Planning," *Transportation Research Part E: Logistics and Transportation Review*, Vol. 48, No. 3, 2012, pp. 591–602. https://doi.org/10.1016/j.tre.2011.11.003

[12] AL-Taharwa, I., Sheta, A., and Al-Weshah, M., "A Mobile Robot Path Planning Using Genetic Algorithm," *Journal of Computer Science*, Vol. 4, No. 4, 2008, pp. 341–344. https://doi.org/10.3844/jcssp.2008.341.344.

[13] Roy, N., Burgard, W., Fox, D., and Thrun, S., "Coastal Navigation-Mobile Robot Navigation with Uncertainty in Dynamic Environments," *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C),* Vol. 1, IEEE, New York, 1999, pp. 35–40. https://doi.org/10.1109/ROBOT.1999.769927

[14] Zhu, Q., and Zhang, Y., "An Ant Colony Algorithm Based on Grid Method for Mobile Robot Path Planning," *Robot*, Vol. 27, No. 2, 2005, pp. 132–136.

[15] Yang, S. X., and Meng, M., "An Efficient Neural Network Approach to Dynamic Robot Motion Planning," *Neural Networks*, Vol. 13, No. 2, 2000, pp. 143–148. https://doi.org/10.1016/S0893-6080(99)00103-3

[16] Kobayashi, K., Okuno, Y., and Ishii, H., "Development of Disaster Relief Aircraft Information Sharing Network," *53rd Aircraft Symposium*, Japan Soc. for Aeronautical and Space Sciences (JSASS) Paper 2F07, 2015.

[17] Andreeva-Mori, A., Kobayashi, K., Shindo, M., and Okuno, Y., "Design and Preliminary Evaluation of an Integrated Aircraft Operation System for Disaster Relief," *Congress of the International Council of the Aeronautical Sciences*, Korean Soc. for Aeronautical and Space Sciences (KSAS) Paper 88, 2016.

[18] "Ehime Prefecture 2018 Disaster Drill Report (in Japanese)," Ehime Prefecture, https://www.pref.ehime.jp/h15550/kunren/h30/documents/01kunrengaiyo.pdf [retrieved 1 Sept. 2020].

[19] "enRoute Drone," https://enroute.co.jp/products/qc730/ [retrieved 1 Sept. 2020].

[20] "JAXA's Research Helicopter," Japan Aerospace Exploration Agency, http://www.aero.jaxa.jp/publication/pamphlets/pdf/heli.pdf [retrieved 21 Feb. 2020].

J. Kuchar
Associate Editor