Help is on the Way: Opportunities and Challenges of Novel Rotorcraft and Associated Systems for Disaster Relief and Emergency Response

Larry Young
Aerospace Engineer
NASA Ames Research Center
Moffett Field, CA, U.S.

Kristen Kallstrom
Aerospace Engineer
NASA Ames Research Center
Moffett Field, CA, U.S.

Sarah Conley
Aerospace Engineer
NASA Ames Research Center
Moffett Field, CA, U.S.

Dorsa Shirazi
Aerospace Engineer
NASA Ames Research Center
Moffett Field, CA, U.S.

ABSTRACT

This paper considers the opportunities and challenges of supporting Disaster Relief and Emergency Response (DRER) missions employing new aerial vehicle and systems concepts. This paper is a broad survey of the possible aerial-vehicle-assisted approaches to aid in DRER missions. The intent of this paper is to elevate this DRER mission application domain as a critical area of investigation for rotorcraft, robotics, intelligent systems, and other research. Current work is primarily focused on assessing air space integration challenges for Commercial Off-The-Shelf (COTS) aerial platforms (typically small multirotor drones and/or small fixed-wing uncrewed aerial vehicles (UAVs)) in disasters such as earthquakes and wildfires. Though this is an important area of investigation, truly efficient and effective DRER systems and response efforts will not be possible without the development of novel aircraft, technologies, and system architectures of COTS DRER drones/UAVs. This paper seeks to address that knowledge gap and encourage government, academia, and industry to pursue DRER mission research.

NOMENCLATURE

AI	artificial intelligence
ACERO	advanced capabilities for emergency response operations
ARMD	Aeronautics Research Mission Directorate
CALFIRE	California Dept. of Forestry & Fire Protection
CONOPS	concept of operations
COTS	commercial off-the-shelf
DRER	disaster relief and emergency response
eCTOL	electric conventional take-off and landing
eSTOL	electric short take-off and landing aircraft
eVTOL	electric vertical take-off and landing
FAA	Federal Aviation Administration
JAXA	Japan Aerospace Exploration Agency
ML	machine learning
PAMS	portable airspace management system
RRD	robotic rescue devices
RVLT	revolutionary vertical lift technology
SOA	State-of-the-art
SAR	search and rescue
UAV	uncrewed aerial vehicles
UAM	urban air mobility
USFS	United States Fire Service
VAERA	VTOL analysis for emergency response applications
VTOL	vertical take-off and landing

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BACKGROUND

The "golden hour" refers to the critical time after a disaster during which effective action can most drastically improve the chance of survival or overall outcome, typically considered to be within the first hour. The rapid development of uncrewed aerial vehicles (UAVs) suggests, at some point soon, the possibility exists that these aircraft could respond within the "golden hour" (e.g. Ref. 1) anywhere in the continental United States or, for international disasters, respond within twenty-four hours anywhere in the world (e.g. Ref. 2). Reference 3 provides some background information on the magnitude of emergency responses circa the early 2000s. Undoubtedly, the demand for disaster relief and emergency response (DRER) missions has only grown since those times. The recent wildfires in California, Oregon, North Carolina, and parts of Canada over the past year are only one set of examples of this growing need. It is argued in this paper that new technologies and novel vehicle and system designs will be a key aspect of enhancing disaster relief and emergency response in the future.

The NASA Ames Rotorcraft Aeromechanics Office has for over two decades performed studies into UAVs – especially, but not exclusively, rotary-wing UAVs – for DRER missions. Early examples of NASA Ames work in the DRER application domain include Refs. 3-12. The early NASA

Ames work was generally performed by, or sponsored by, the Ames Rotorcraft Aeromechanics Office and, accordingly, was generally vehicle centric. A few of these early papers, provided discussion related to the notional interplay of networks of vehicles and (robotic) systems to perform DRER missions; this work has become increasing relevant over the past twenty-plus years as tremendous advances in robotics, information, and autonomous system technologies have been made over these years.

Over the past 6+ years, a small group of NASA Ames Aeromechanics Office early career researchers initiated the VTOL Analysis for Emergency Response Applications (VAERA) effort to enable the design, analysis, and development of rotorcraft for DRER scenarios, both for crewed and uncrewed vehicles. The first published VAERA paper, Ref. 13, helps to identify technology gaps for wildfire relief rotorcraft missions. With their initial efforts focused on wildfire relief missions, the VAERA team has also devoted efforts to other DRER missions. VAERA and its modeling and tool development work is one of the topics discussed in this paper.

The Advanced Capabilities for Emergency Response Operations (ACERO) project is a major DRER-related project funded by the NASA Aeronautics Research Mission Directorate (ARMD). The ACERO project's goal is to create infrastructure to support and enhance air traffic control support in wildfire zones, in collaboration with the Federal Aviation Administration (FAA), United States Forest Service (USFS), the California Department of Forestry and Fire Protection (CAL FIRE), and international partners, such as the Japan Aerospace Exploration Agency (JAXA), Ref. 14. ACERO has been making great progress in the development of the Portable Airspace Management System (PAMS) and has performed several flight tests in collaboration with CAL FIRE, Ref. 15. The ACERO team also explored CONOPS (concept of operations) for wildland fire management, with extensive background research completed to determine the current state of wildland fires in the United States, as well as mitigation strategies and how to potentially improve the future state of wildland fire prevention efforts, Ref. 16.

An early suggestion for possible public/private partnerships was introduced seven years ago, in the form of a civil reserve air fleet for emergency/delivery drones, Ref. 4. Since then, delivery drone, Urban Air Mobility (UAM), and electric vertical take-off and landing (eVTOL) technologies and services have undergone substantial advances – and, unfortunately during this time frame, many disasters have devastatingly struck the United States. There have been tremendous advancements in non-aviation technologies that are potentially applicable (in a system-of-systems solution approach), including:

- automated warehouses and logistics
- ground delivery robotic systems
- self-driving automobiles/taxis
- AI (Artificial Intelligence)/Big Data analytics (including cellular services, cell phone apps, and wearable devices)

It should be noted, though, that while the DRER problem might benefit from the above automation advancements, the DRER problem nonetheless presents challenges for UAVs that do not occur in the above listed system-of-systems problems. Disaster response scenarios usually occur in highly unpredictable environments as opposed to more controlled environments like automated warehouses and logistics. Even though self-driving vehicles occur in a more challenging environment, companies deploy fleets of vehicles into the environment to collect massive amounts of data. There are DRER scenarios do not occur frequently enough to query them for data; for example, the recent large-scale power outage (including traffic lights not operating) in San Francisco had a major adverse impact on self-driving taxis operating, Ref. 17, simply because such a major outrage has been an infrequent event. DRER responses can also occur in harsh environments, especially with natural disasters, which can affect vehicle response, and pilot/autonomy visibility/sensor reliability. Moreover, humans are almost surely to be involved in DRER scenarios, likely in distress, and modeling human behavior and accounting for human safety under such conditions for autonomous systems would also present a challenge. Despite such challenges, the opportunity to have a major positive impact on DRER missions is one that cannot be ignored. Of additional interest, Refs. 18-28 are high-level survey papers of past and possible future drone applications for emergency and disaster relief mission applications.

Table 1 summarizes several potential technology gaps for the use of UAVs or drones for DRER missions and how the technology gaps should be addressed.

Table 1. Technology Gaps for DRER UAVs/Drones.

1	Range and speed of COTS or SOA (state of the art) UAVs needs to increase (advances in aerodynamics, propulsion, and aircraft design required).
2	The payload capacity needs to be increased to carry more aid or, alternatively, heavier rescue equipment (advances in aerodynamics and aircraft design required).
3	More sophisticated and powerful sensors need to be integrated into UAV guidance, navigation, and control for search and rescue operations (advances in sensors, instrumentation, and autonomous system technologies required).
4	Rescue and relief resources should be placed closer to extant or disaster or emergency sites while taking care to minimize logistics footprints for DRER missions (advances in communication, robotics, and autonomous system technologies required).

Additional considerations for this effort is discussed below. Whole-of-community or, rather, whole-of-society resources should be drawn upon in an efficient and effective coordinated manner (advances in internet-of-things information technology required). UAVs and drones and their platforms could become (semi-) autonomous command and control nexuses for entire ecosystems of robotic or autonomous rescue devices or equipment. Furthermore, tailoring aerial operations could minimize adversely disturbing rescue sites.

Tackling the problem of expanding the response efforts to a complete spectrum of emergencies and disasters requires a true system-of-systems solution approach that draws in many stakeholders and many different technologies and disciplines. For clarity, in the context of this paper, the system-of-systems architecture discussion is attempting to define a high-level framework (architecture) that encompasses multiple systems of high complexity that need to work effectively and cooperatively together (a system-of-systems) to solve a global problem. For example, the success of an emergency response system is not simply a question of aerial vehicle design, but it also requires ground-based support equipment and facilities, a nominal and off nominal CONOPS, and a communication and coordination system (aka network) between all involved parties in an emergency. It also needs a contractual protocol if commercial systems are going to be dragooned into service as emergency systems. The system-of-systems approach emphasizes the value of various independent concepts that contribute and work together towards the goal of improving DRER. This work is an exploration of various missions, novel concepts, and sentinel networks that would contribute to an overarching DRER system-of-systems architecture.

MISSION OPPORTUNITIES AND CHALLENGES

In this section, several mission examples of using UAVs and advanced aerial vehicles are presented along with various considerations and challenges. Additionally, aspects of carrying out smaller and larger scale missions are considered.

Mission Examples

This section serves to provide a few examples of the types of DRER missions that could be accomplished and various challenges and considerations.

<u>Post Earthquake</u>

Mission: Emergency responders can deploy small drones to safely investigate buildings after an earthquake to look for survivors and to assess the structural integrity of the building to determine if it is safe to enter.

Considerations/Challenges: Equipping the drone with infrared sensors would help to detect people faster if they are covered in debris. A speaker and microphone would allow the drone to communicate directly with any survivors. A light could help the drone lead people safely out of a building. Having ducted or caged rotors would reduce the risk of rotors accidentally injuring humans or getting damaged by striking objects.

Note that a research group has already begun work on the development of a UAS platform for indoor search and rescue (SAR) missions like this one, Ref. 29. This work suggests having one UAS perform reconnaissance while the other focuses on 3D mapping.

<u>Post Hurricane, Storm, Tornado, Tsunami</u>

Mission: The first mission is for aerial vehicles to help clean up debris and clear up roads/pathways. The second mission is to provide surveillance of the situation and look for survivors. The third mission is to assist in an active rescue of survivors.

Considerations/Challenges: For the first mission, to clean up debris, a vehicle with claws or the ability to grab items (e.g. Refs. 30-32) would allow the vehicle to be uncrewed. This would enable the vehicle to enter inaccessible areas or areas too dangerous for first responders, reducing risk to personnel. Additionally, for all these missions, having floatable landing gear would allow the vehicle to rest on the water in between flights.

An infrared sensor would be valuable in searching for survivors. For the third mission of assisting in an active rescue, an uncrewed vehicle could carry lifejackets, inflatable rafts, thermal blankets, food, and/or water. If the vehicle is crewed, then the vehicle would need to be much larger with a greater payload capacity. The crewed vehicle would need a minimum of one pilot, one emergency services person to help perform the rescue, and additional payload for carrying survivor(s). It may be worth exploring whether certain rescues can be at least partially automated, e.g. Ref. 33.

One of the ongoing challenges for aerial vehicles is improving their ability to operate under extreme weather conditions. Until vehicle performance and handling capabilities are significantly increased, it is not safe or feasible to fly during the extreme weather. To account for this, the outlined missions below are focused on providing support in the early hours after the disaster, once the weather allows for safe flight. Increasing the capability of rotorcraft to fly in extreme weather conditions is one of the many technical challenges for future DRER research efforts. Some past work investigating the impact of extreme weather on drone or UAV operations is noted in Refs. 34-37. Note that increasing the extreme weather capabilities of drones and UAVs has implications for not only DRER missions but also for field science campaigns and other public good missions.

<u>Humanitarian Aid</u>

Mission: Deliver food, water, and/or medical supplies to those in need. This includes communities struck by natural disasters, extreme weather, food or water shortages, etc. This can be applied to both local and major disasters (discussed later in the Disaster Scale Considerations section).

Considerations/Challenges: One of the main challenges with this mission involves how to accurately, safely, and reliably perform the payload delivery. In favorable conditions, the vehicle could touch down in the landing zone, have either an automatic or a manual release of the package, and then take off. If there isn't a safe landing zone, the vehicle could fly low and release the package from a safe altitude. However, flying low introduces complications from outwash and downwash and could potentially cause the vehicle to become unstable. Another possibility is to release the payload from a specific height range with a parachute or cushioning to keep the supplies from being damaged. This method might not be viable in extremely windy conditions or environments with many trees/buildings/obstacles. The type of delivery approach will also have implications for the packaging of the delivered supplies. It is important that the supplies are packaged in a way that protects the supplies from damage, but they also need to be easily and intuitively openable without tools (i.e. no knife or scissors needed), since tools may not be available.

Disaster Scale Considerations

The previous section shows that there is a wide range of missions for various disasters and emergencies that can be addressed by rotorcraft. Disasters of different scales have different operational considerations. Some disasters could be major or local depending on their scale. Major disasters include large scale events like earthquakes, hurricanes, storms, tornadoes, tsunamis, and wildfires. In contrast, smaller scale local disasters may encompass events such as transport emergencies (car crashes, train derailments, ship sinkings, etc.), small scale humanitarian responses (food and medical aid), mudslides, avalanches, urban fires, or chronic situational aid (such as responses to drug overdoses or cold weather assistance for the unhoused).

The distinction between a major and a local disaster is based on scale and impact; each natural disaster can be classified as either major or local, depending on its widespread effect. The major disaster requires extensive resources and coordination and can involve local, state, and federal agencies. A local disaster is a smaller scale event that may not have the same impact as a major disaster but can still require similar emergency services. Local disasters often rely on local and regional first responders. For most disaster events no matter the scale, it is normally the local first responders that arrive on scene first before state and federal personnel. It is important to consider this when determining where emergency service funding should go or who should have access to DRER aerial vehicles.

Subsequent discussion in the paper illustrates the need for different types of vehicles, as well as their potential impact on improving SAR scenarios for both a local and a major disaster.

Storyboard One - Local Disaster

An example of a routine emergency response for a local disaster is when outlying neighborhoods in a metropolitan area experience flooding, as described in Reference 4. Longer-range UAVs can be deployed to conduct a large-area initial assessment. Meanwhile, civilian and first-responder small UAVs could be stationed at various critical locations within the affected neighborhoods. These small UAVs could assist with dedicated SAR missions, providing situational guidance for subsequent ground and air rescue operations conducted by crewed assets. Additionally, higher-altitude, longer-endurance UAVs could be used as temporary telecommunications support, Ref. 38.

Storyboard Two - Major Disaster

An example of a major disaster response (Ref. 4) is when a major earthquake has struck a large metropolitan area. First responder assets including small autonomous SAR aerial vehicles can perform initial surveys of the damaged areas. The imagery can then be transferred to network/cloud-based data analysis systems which prioritize first-responder neighborhood response. An automated emergency call-for-action can then be sent out to volunteer commercial and civilian UAV operators as per a pre-existing DRER UAV registry and pre-established aid agreements. Civilian and commercial UAVs can coordinate operations with first-responder agencies to provide SAR and small aid package delivery to those in need. Disaster victims and relief requirements established by smart-phone and digital device can contact the victims and/or perform automated relief assessments through network/cloud database analysis.

INNOVATIVE VEHICLE DESIGNS

Vehicle Considerations

There are certain considerations for each aerial vehicle carrying out each mission. These include environmental conditions the vehicle will be subjected to (i.e. temperature, wind, gusts, visibility, humidity, precipitation) as well as the airspace environment. It is important to ensure that UAVs are not interfering with or creating an unsafe environment for crewed vehicles. For example, if there are crewed vehicles performing water drops on a wildfire, it is unlikely that any uncrewed vehicles could safely operate in that airspace – unless there are major technology advances to collision avoidance systems, vehicle-to-vehicle situational awareness networking, and a major cultural shift – since such uncrewed air traffic could slow down the crewed vehicles, or worse, cause accidents. If there are areas, though, in which the crewed vehicles cannot or will not go (i.e. unsafe flying conditions), then the uncrewed vehicles should make that their priority. There have been several proposed concepts on using drone swarms for various missions, e.g. to help put out wildfires. While using drone swarms for such a mission may be theoretically possible, the number of drones needed for the airspace and the monopolization of UAVs in the airspace makes this mission proposal problematic. It is important to consider the emergency response system as a hole, including considerations for safety and cost, rather than just solely focusing on what an uncrewed vehicle could theoretically perform or accomplish.

So, when is it useful to have an uncrewed aerial vehicle rather than a crewed vehicle? The robotics and autonomous system research communities came up with the three D's to help answer this question: Dull, Dirty, and Dangerous (e.g. Ref. 39). If a mission is Dull, Dirty, and/or Dangerous, having an uncrewed aerial vehicle may be more desired.

Multi-Use Rotorcraft

There are several potential dual- or multi-use (military versus civilian public good) applications including: surveillance (aka aerial surveys), resupply (aka aid deployment), distributed dispersal of chemicals (e.g., fire retardant), sensors, and devices. Many dual-use DRER applications are discussed in another paper, also presented at this conference, Ref. 40. The term 'dual use' typically refers to rotorcraft that could be used for military and civilian missions. 'Multi-use' is used in the context of this paper as differentiating between civilian missions that fall into public service and/or public good categories and those that fall within commercial categories.

Reconfigurable vehicles (for cabin interiors or external stores) could be utilized for multiple missions which would significantly save costs and allow for a larger fleet of vehicles at the ready. If industry or commercial aerial vehicles could be used for DRER missions on an as needed basis, that would drastically increase the potential scale of the response. Reconfigurable UAVs that can trade payload for endurance would be ideal for multi-use situations. For example, when performing a surveillance mission, the payload would be decreased for higher endurance, and then the payload would be increased when performing a shorter distance supply drop mission. Additionally, the payloads that these aircraft can carry to support DRER supply drop missions may overlap across different scenarios, further increasing the aircraft's multi-use capability.

Though there are many opportunities in considering dual- and multi-use applications for DRER aircraft, there are also potential disadvantages. If one use case overly dominates the aircraft development, then the general applicability to other uses will likely be diminished. Additionally, certain DRER missions require vehicles to be very robust and able to withstand harsh weather conditions. For example, a UAV used for fighting wildfires would need to have cooling capabilities, whereas a UAV used for avalanche missions in snowy areas would need the opposite. Also, both of those use cases would likely need the UAV to have the ability to perform well in extremely windy and turbulent conditions whereas a UAV for humanitarian aid might not have this requirement. A common industry delivery drone may not have the ability to be retrofitted to perform missions in those extreme environments. Preserving a multi-use balance is imperative but, at the same time, difficult to manage. Figure 1 gives an example of the supply delivery mission across civilian, military, and public good domains. Civilian, military, and public good technologies and vehicles can benefit from and help improve each other. This is a major discussion in Ref. 40.

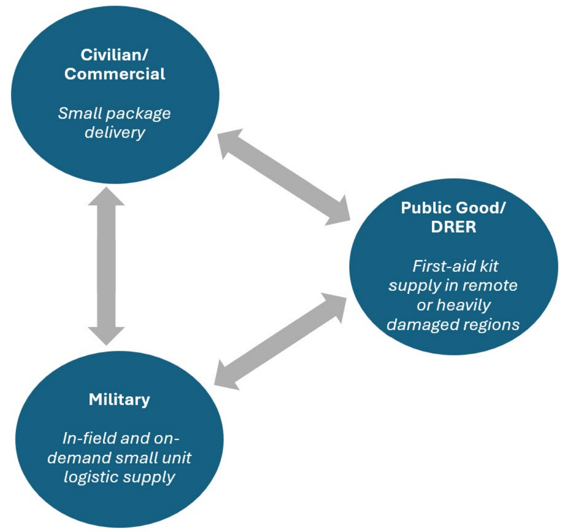

Figure 1. Multi-use (military, commercial, and public good) applications of rotorcraft and/or drones.

The remainder of this section will introduce a few different representative vehicle design concepts and their design considerations to further to illustrate the potential for future vehicle innovation with regards to DRER missions. Each design concept introduced falls into one or more of the four vehicle innovation drivers identified in Figure 2.

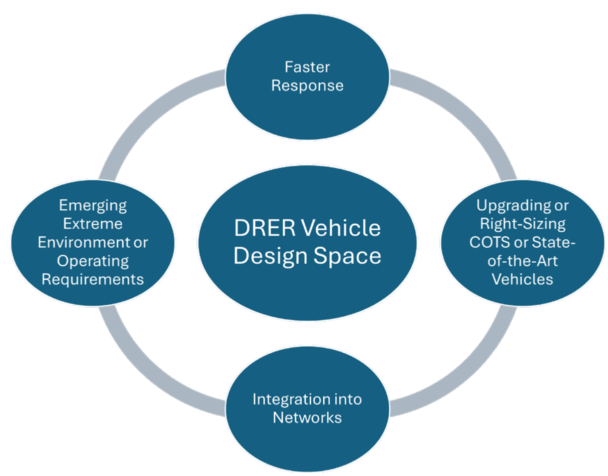

Figure 2. Illustrative examples to help define an expanded DRER vehicle design space.

Santa Ana ('Devil Wind') Flyers

This section presents a conceptual design for the "Santa Ana Flyer," also referred to as the "Devil Wind Flyer," to improve and optimize launch and recovery within wind speed limits. The Santa Ana devil winds are harsh, dry, and hot winds that occur in Southern California, Ref. 41. This wind phenomenon can cause dramatic increases in wind velocity and exacerbate wild/brush fires and pose flight challenges to emergency responders. The Devil Wind Flyer concept is a proposed advancement that aims to overcome the current limitations of conventional rotorcraft, particularly rotary-wing UAVs. The strawman design considerations of this Devil Wind Flyer concept are detailed below.

Strawman Design Considerations:

1. Overall vehicle configuration symmetry should be incorporated to minimize sensitivity to crosswinds.
   a. This could result in difficulties 'streamlining' the aircraft fuselage/hull or result in more 'bluff body' type hulls and increase vehicle downloading in hover and vehicle drag (and moments) in forward flight.
   b. Configuration symmetry might be heavily influenced by rotor-on-rotor or rotor-on-fuselage interactional aerodynamics in forward flight; such interactional aerodynamics should be fully considered and mitigated to achieve not only geometric symmetry but also aerodynamic symmetry.
2. Aerial vehicles should be transportable via cargo flatbed trucks or rail cars to reposition before, during, and after storms.
3. Landing gear should be designed to successfully land in high winds or launch/landing points protected by windbreaks would be required.
4. Aerial vehicle guidance, navigation, and control (GNC) should be agnostic to direction of travel relative to vehicle reference axes.
5. An ability to successfully 'tack' (maintain general course) into high winds, including high crosswinds, while in flight is required, Figure 3. It is insufficient to be semi-passively carried along by the winds (with positioning of launch sites); the vehicles are not 'balloons' that drop payloads mid-drift.
6. Two missions for the aerial vehicle can be considered: (a) fire-retardant/water drop vehicle and (b) an emergency rescue/recovery mission. (i.e. the design should accommodate swapping out a retardant storage container with a rescue basket/stretcher).
7. Size tradeoff for the aerial vehicle: the smaller, lighter the vehicle the more likely that the vehicle will be subject to large disturbances by the winds and gusts; with larger, heavier vehicles there will be increased acquisition costs as well as increased mission resilience to possible hull/vehicle loss during a high-risk mission/flight.
8. Rigid rotors/propellers with higher blade count and higher disk loading may be required to ensure effective performance in high winds/gusts.
9. More unconventional rotor systems, such as constant-lift rotors (e.g. 'Stroub propellers'), might be required for operation in high winds/gusts to avoid high rotor hub moments stemming from nonuniform and sudden transient aero loading over the rotors/propellers.
10. Stall resistant or benign stall airfoils might be considered for rotor/propeller blades.

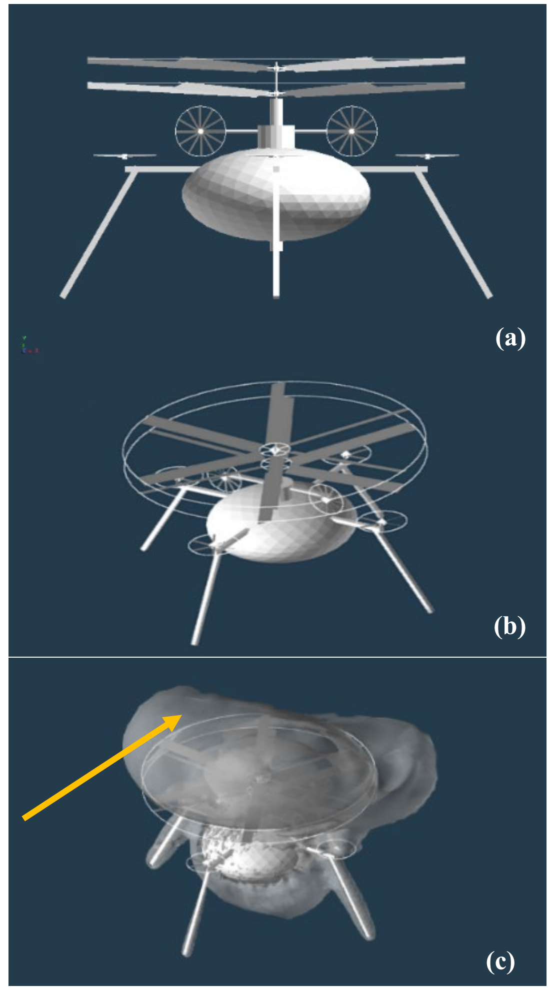

Figure 3. Notional Strawman Rotorcraft 'Santa Ana Flyer': (a) front view, (b) isometric view; (c) forward flight, 180ft/s or μ=0.3. (Note propulsors are on a pivoting wing to allow 'tacking' into the wind).

Notional mission profile for any Santa Ana Flyer-related study:

1. Total mission range to be 75 nm with fire-retardant drop occurring at the mission halfway point.
2. The fire retardant 'payload' mass is to be 20% of the total takeoff gross weight.
   a. Requiring a mass fraction rather than a required payload mass in kilograms is to allow a broad range of vehicle sizes to be considered for the overall wildfire suppression campaign.

Because different vehicle sizes may be evaluated, a system-of-systems level analysis is also necessary to assess the daily volumes of fire retardant dispensed by various fleets. This includes examining whether a larger number of smaller aerial vehicles provides better performance than a smaller number of larger vehicles.

Figure 4 illustrates an example of 'Stroub' constant-lift propellers (for precursor work, refer to Refs. 42-44) which may be more resistant to gust perturbations as compared to conventional fixed-pitch propellers for multi-rotor vehicles. The torsion rod is tapered to carry the centrifugal forces of the blades. The taper of the torsion rod (and matching taper bore for the split hub(s)) allows for free-pitching of the blade assembly as well as tensile-capture of the torsion rod. A tapered bore surface would have solid lubricant applied, and the bore surface should ideally see minimal normal force loading due to proper balancing between respective opposing blades.

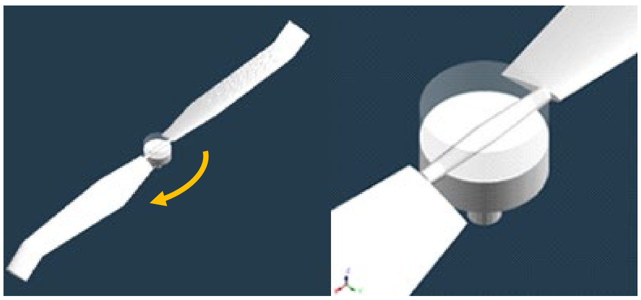

Figure 4. Overview of Stroub constant-lift propeller, with the rotor shown on the left and the hub on the right.

Littoral Relief Supply Mission with Amphibious or Shipboard-compatible Rotorcraft

A study of disaster relief missions where supplies are ferried from an offshore ship to urban regions along littoral (near ocean or large body of water) coasts for large national and international disasters is considered. Such a mission could be consistent with a spinoff of the NASA UAM quadrotor reference design, Ref. 45. A clean cabin can be utilized for stowing supplies, helping avoid unnecessary weight on equipment and making the aircraft range more manageable. Additionally, electric vehicles (no gas) might be safer to operate around collapsed buildings and/or gas leaks. If the platform were to be fully autonomous, instead of the added weight of a pilot, the weight could go towards additional auxiliary batteries or extra supplies.

Collaboration between NASA, Coast Guard, and industry could lead to subscale NASA Reference Design and/or industry eVTOL tech/op demonstrations of littoral (from ship to shore) aid supply for earthquake and/or tsunami relief. Flight testing conducted of a (near-) production UAM/eVTOL vehicle as a flight demonstrator would be invaluable for establishing the use case of a UAM flying aid from an offshore coast guard ship or cargo/supply ship to city centers and back again. Figure 5 provides an image of the simulation for this mission employing UAM-derivatives and mid-fidelity CFD predictions of aerial vehicle and ship wakes (details of the CFD solver used can be found in Ref. 46).

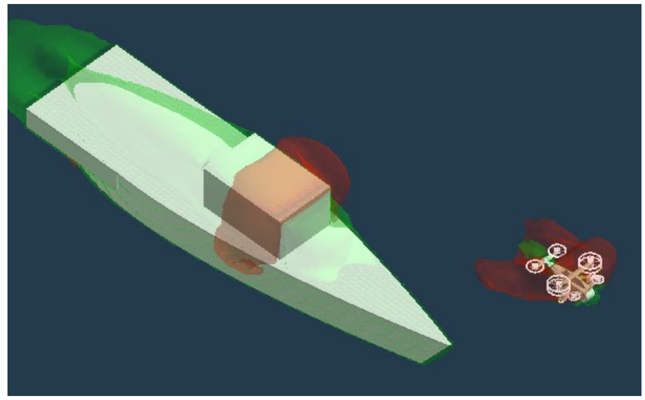

Figure 5. Mid-fidelity CFD (velocity magnitude isosurfaces) of notional littoral resupply with cargo version of eVTOL conceptual design from Ref. 38.

Fast Response Vehicles

The potential to expand upon the capabilities of existing crewed utility-type helicopters such as the Sikorsky UH-60 for DRER missions, has already started, e.g. the LA County 'Firehawk', e.g. Ref. 47. Recently, an uncrewed version of the UH-60 has been proposed that could carry large volumes of payload, e.g. Ref. 48. A case can also be made to develop new generations of novel vehicles that are tailored to stow, carry, deploy, and control robotic rescue devices for missions in which success is contingent on the efficient and effective operation of both the aerial vehicle and the robotics rescue systems required for those missions.

In 2006, several NASA Ames concepts for both crewed and uncrewed vertical lift aerial vehicles that could support and enable expanded DRER roles were presented, Ref. 4. This early work explored potential mission concepts and proposed notional and novel vehicle designs that could apply for DRER applications. Additionally, this work also took a system analysis approach to DRER research and proposed a methodology that characterizes a range of solutions for various disaster relief scenarios.

A potential new design space for DRER dedicated vehicles lies between the small UAVs, multirotor drone platforms, and the emerging eVTOL vehicles recently explored by NASA and currently being developed by industry. Figures 6 and Figure 7 are two such concept vehicles depicting multirotor tilt duct configurations designed for DRER missions and further explored in Ref. 49.

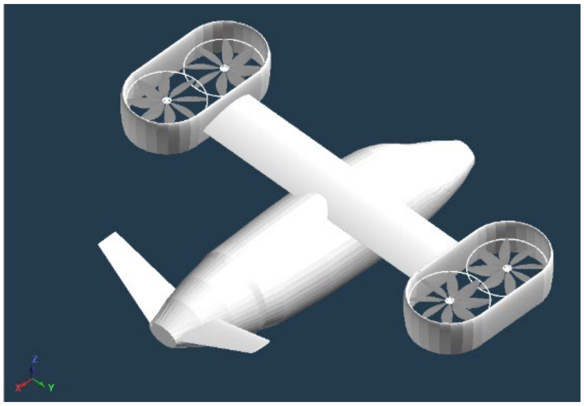

Figure 6. Novel tilt duct DRER vertical lift vehicles (concept discussed in Ref. 49).

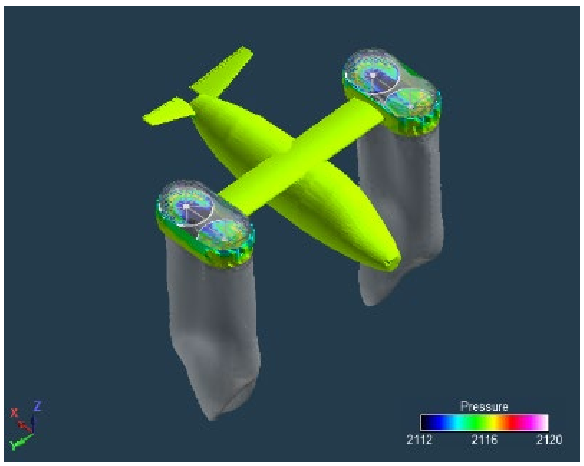

Figure 7. Mid-fidelity CFD (hover) of a novel tilt duct DRER vehicle (concept discussed in Ref. 49, CFD solver described in Ref. 46).

INNOVATIVE NETWORKS

The aerospace industry thrives on innovation and ingenuity. Design and technology innovation is the key to continued growth and the overall health of the rotorcraft industry. With global increases in environmental catastrophes, rotorcraft provide a unique medium to improve disaster response capabilities. But obviously, rotorcraft alone are not the complete solution for efficient and effective disaster relief. Even in today's world, rotorcraft and aerial vehicles are just one element in networks of (communication, coordination, and logistics) systems, trained specialized personnel, supporting relief organizations of many types, and overall integrated operational processes and procedures. Therefore, to greatly improve disaster relief and emergency in the future it will be necessary to do more than just pursue vehicle design innovation. It will be just as important to consider development and implementation of innovative DRER networks in addition to new, higher-capability aerial vehicle designs. Such future innovative DRER networks should reflect not only anticipated advances in aerial vehicle capabilities but should also reflect advances in self-driving ground vehicles, robotics, autonomous system and information technologies, satellite and cellular communication, 'internet of things' services, and cloud-computing. Specifically, with regards to defining possible future innovative DRER networks, this paper discusses three sets of technologies that might need to be considered for future DRER missions: novel system-of-systems architectures (including the introduced 'Safety Net' concept), 'sentinel networks', and robotic rescue devices. All these suggested potential DRER network technologies would be enabled in some part by rotorcraft.

Figure 8 illustrates the current main innovation drivers for DRER networks. There are six drivers of which only two are directly related to advances in rotorcraft technologies. Incorporating all six technology drivers in future DRER networks could, though, result in major holistic advances in DRER missions.

Figure 8. DRER network innovation drivers

Current DRER research within NASA is primarily investigating the use of COTS drones or small UAVs; the focus of such research is mostly on UAV traffic management (UTM) tools and CONOPS, Refs. 14-16. There are four research areas of interest that will be explored in this section that encourage engineering innovations for DRER applications: (a) system-of-systems architectures; (b) sentinel networks; (c) rotorcraft and robotic rescue devices; and (d) safety net.

System-of-Systems Architectures

Reference 4 was among the first introductions to new types of system-of-systems architectures to address increasing demands for disaster rescue and relief. The Smart Precise Rotorcraft Interconnected Emergency Services (SPRITES) concept includes notional vehicle concepts that could be part of a network of autonomous emergency response vehicles.

The SPRITES paper further explored scenarios and storyboards for SAR efforts. New missions and CONOPS will ultimately be the driving forces for adopting vehicle, robotic system, and system architecture innovations within the DRER application domain. One such system architecture concept that could support both vehicle and robotic system networks is a sentinel network.

Sentinel Networks

A sentinel network is the concept of autonomous warehouses, or aircraft hangars, that house networks and/or systems of drones, including robotic rescue devices and autonomous rotorcraft, that are ready to be deployed in emergency response scenarios. Sentinel networks were first described in Ref. 3. A sentinel network could provide sustained aerial presence in both urban and rural communities. Development of these sentinel networks would require some human guidance for initial applications to ensure the system works reliably, with the goal being that an autonomous aerial presence could in the future complete missions with minimal human interaction.

One of the key challenges to the development of sentinel networks, or other types of aerial vehicle and automated hangar applications, is how to provide sustained aerial and surface interactive presence. There are many potentially critical application domains and mission scenarios to consider for sentinel network implementation – such scenarios were previously discussed in the Mission Opportunities and Challenges section. Further storyboards are explored in the Rotorcraft and Robotic Rescue Devices section.

To meet this challenge, a suite of technologies should be identified and developed, including aircraft/VTOL vehicle designs, robotics, and intelligent systems. Identification and development of such technologies would enable the implementation of a system-of-systems architecture, such as the sentinel network, capable of mission completion for several different DRER applications. Some examples of autonomous (VTOL) aerial vehicle and automated hangar/station networks include: sentinel networks for localized wildfire response at the earliest stages of fire breakout; 'Terrestrial Extreme Environment Explorer (TE3)' networks (sustained remote site terrestrial field science campaigns); and wildlife conservation stations. Figure 9a-c includes concepts and preliminary flow analyses of VTOL fire spotter vehicles departing from a conceptual sentinel network automated station. Figure 9a shows an example of a VTOL fire spotter hovering in ground effect (HIGE) over the hangar pad. Figure 9b depicts a rotorcraft HIGE offset laterally from the hangar pad. Figure 9c shows a VTOL fire spotter hovering out of ground effect (HOGE) near the hangar. By having such automated hanger/fire-stations sited in key wildfire areas, the response time to suppress fires would be reduced by two factors: the speed of the aerial vehicles and siting of the automated stations in key wildfire-prone areas.

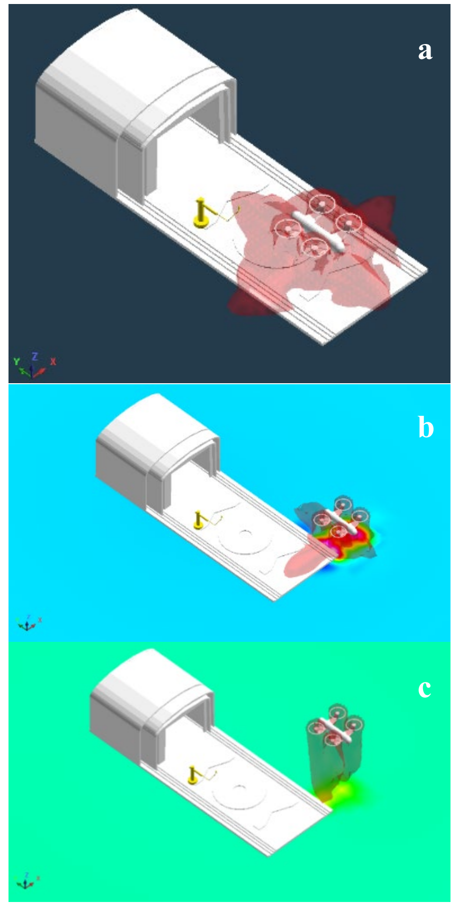

Figure 9. Sentinel Network 'fire spotter' and autonomous hanger: (a) HIGE over hanger pad, (b) HIGE laterally offset from hangar pad, and (c) HOGE laterally offset from hangar pad.

Development of successful DRER solutions, including novel vehicle designs, system-of-systems, and autonomous networks will require embracing two or more of these interrelated research areas and their associated concepts and technologies. Focusing on one area of research and neglecting the others could result in inefficient or ineffective solutions.

Rotorcraft and Robotic Rescue Devices

Industry, academia, and government researchers, engineers, and scientists are exploring the capability of rescue robots and drones in a variety of scenarios. Novel robots have been proposed for both urban SAR as well as water rescue. For example, the Soft Pathfinding Observation Unit (SPROUT), a soft "vine" robot concept that may be able to navigate collapsed structures, has been proposed in Refs. 50 and 51. The snake-like structure would allow the robot to fit into small spaces. With respect to water rescues, the Emergency Integrated Lifesaving Lanyard (EMILY) robotic lifeguard was developed under the Small Business Innovative Research (SBIR) program to assist with SAR during marine disasters, Ref. 52. These technological innovations provide just two real-world examples of expanding DRER capabilities with robots – there are many more concepts being developed and deployed through government, industry, and academia collaborations.

An expanded discussion is presented in this paper as related to the early work of Ref. 5. Both novel vertical flight vehicles and novel rescue systems (that might be transported by or substantively interact with the aerial vehicles) need to be developed to enable efficient and effective DRER missions. References 3–12 went into considerable detail discussing the complementary roles of advanced, or novel, aerial vehicles and associated (robotic) rescue/relief systems for various forms and magnitudes of disasters and emergencies.

In the past fifteen years, there has been a significant surge in the development of autonomous vehicles and robotic systems by both academia and industry. These technologies, which were once limited to proof-of-concept demonstrations, are now being deployed in real-world applications. Using aircraft in combination with robotic rescue devices (RRD) increases the likelihood of faster emergency response and greater accuracy. Figure 10 illustrates various design categories for rotorcraft and RRD, as well as a wide range of ground and submersible robotic vehicles.

The notion of rotorcraft working in partnership with RRD for DRER missions was explored by NASA in Refs. 5, 7, and 9. Meanwhile, in parallel, standalone RRD are being actively pursued by academia and small startup companies, e.g., Ref. 53 .

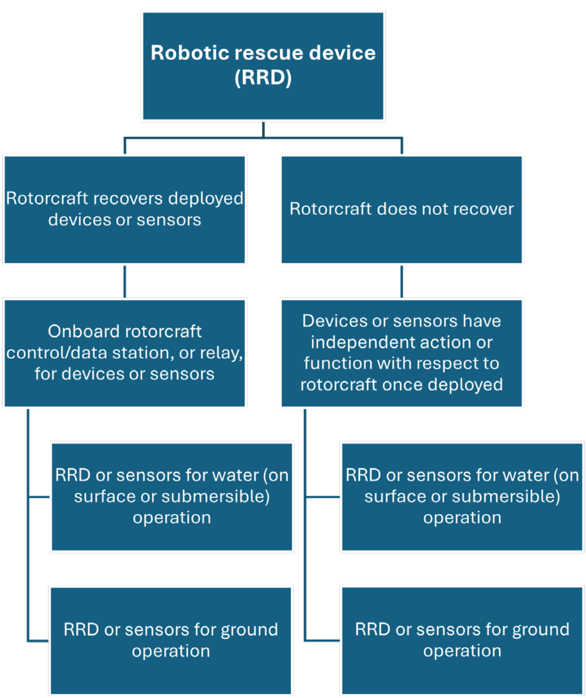

Figure 10. Defining robotic rescue device design space.

Storyboard for Rescue Vector Hoist

In August 2025, a notable hoist rescue was conducted by a helicopter pilot in the Sacramento Metro area of California. The pilot and crew from Metro Fire's Copter 3 successfully rescued an injured hiker by positioning one of the helicopter's skids near the edge of the slope to offload the rescuer. The rescuer then provided initial medical assistance to the hiker and utilized a Bauman bag to help transport the patient from the hiking site into the helicopter. Figure 11 shows a notional image of a DRER aerial vehicle employing a robotic rescue hoist. The hoist has positioning thrusters to swing the hoist from underneath the aircraft towards the sides of high-rise building. A simplified representation of a building is also shown in Fig. 11 with an open window, or exterior opening. The robotic rescue hoist is shown being positioned towards the window for rescue access (see Ref. 9 for a more detailed discussion of such notional robotic rescue hoists).

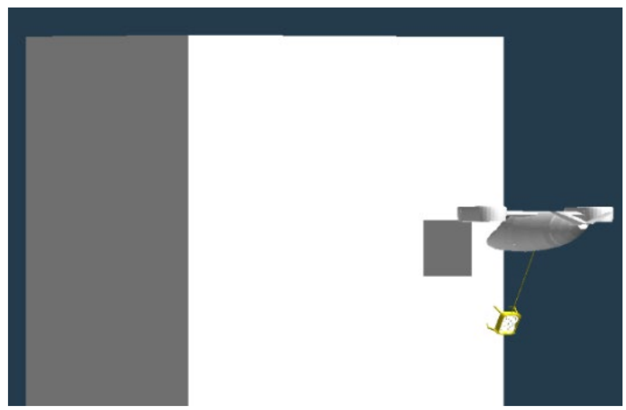

Figure 11. 'Vector' Robotic Rescue Hoist.

Storyboard for Distributed Aerial Searches

Drones and small UAVs can be effectively used to survey large areas, identify hazards, and conduct rescue missions. The development of drone technology, with a focus on battery life and communication among a network of UAVs, has garnered significant interest from academics and researchers (e.g. Ref. 54). These multiple drones and larger aerial vehicles (which might also as carrier aircraft for the drones) are equipped with sensors such as infrared, imaging, and biometer monitoring, to name a few, and can greatly enhance SAR operations. Additionally, as artificial intelligence (AI) continues to advance, the capabilities and operational efficiency of these vehicles are expected to improve significantly, but much further research is needed to make uncrewed operations efficient and accurate. Figure 12 shows a notional example of UAV swarms assisting in large area searches (for more details on the aerial vehicle and the drone concepts shown, refer to Refs. 49 and 55).

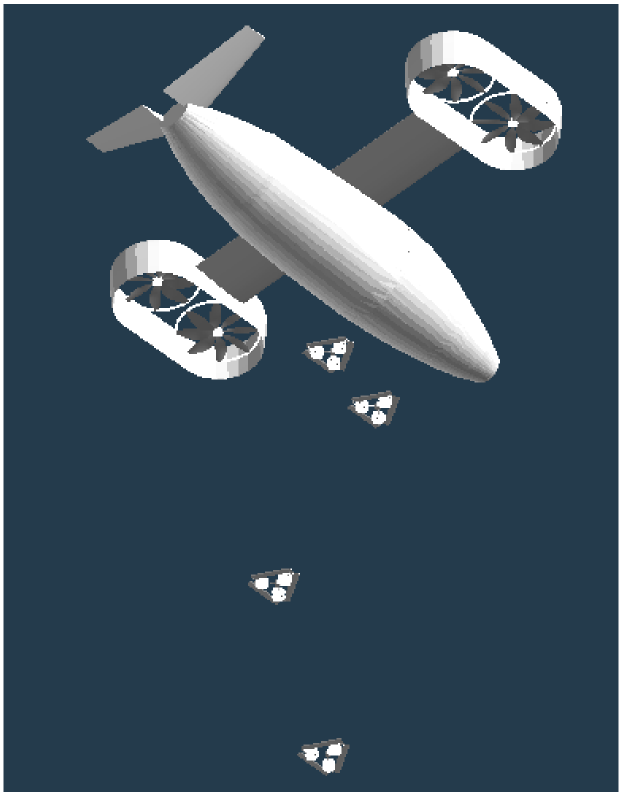

Figure 12. Release of swarms of smaller aerial RRD drones for distributed searches.

Storyboard for Aquatic Rescue

An example of aquatic rescue is the incident in which a passenger fell overboard from a ferry enroute to Martha's Vineyard during a Nor'easter (powerful storm) and was located and rescued by a U.S. Coast Guard helicopter, Refs. 56 and 57. This rescue by helicopter took place while the ferry crew initially identified the subject one nautical mile south of Nobska Light but lost visual contact during recovery operations. This incident highlights the advantage of having an aerial perspective, which can only be achieved through birds-eye view by aircraft operations in such rescue situations. Unmanned surface vehicles (USV) are another very active area of research (e.g. Ref. 58); combining the use of UAVs and USVs to conduct search and rescue missions could leverage the different vehicle embodiments to achieve mission objectives. An example of a novel DRER aerial vehicle deploying a potential robotic rescue raft (unmanned surface vehicle (USV)) is depicted in Figure 13.

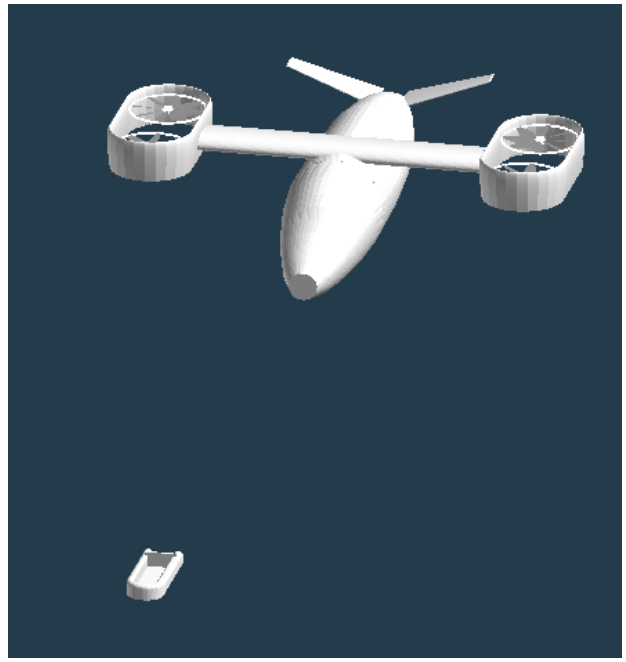

Figure 13. Depiction of a tilt duct aerial vehicle conducting an aquatic RRD rescue.

Alternatively, amphibious rotorcraft (Ref. 59) could also potentially be used for at-sea rescues.

Storyboard for Ground (Mobility) Rescue

Aircraft can be instrumental in quickly locating missing individuals in disaster-stricken areas that are accessible to ground teams. Additionally, aircraft offer a quick and effective means to transport injured individuals, particularly in regions affected by natural disasters. They also have the capacity to deliver a large volume of essential supplies to affected areas, alleviating distribution by ground rescue efforts. The use of autonomous aerial vehicles transporting and deploying robotic ground mobile systems might be a powerful enabler for future rescue missions (e.g. Refs. 60-61).

A notable example of an aircraft used in disaster response occurred in 2025, when NASA sent a high-altitude WB-57 aircraft to Texas as part of its SAR operations during a flood, Figure 14, Ref. 62. The high-altitude WB-57 aircraft was equipped with an airborne motion image sensor designed for terrestrial environments, enabling it to capture high-resolution images that satellites could not. This information was crucial for understanding the impacted area and supporting rescue operations on the ground. It enabled better allocation of ground-level resources and identified inaccessible areas for ground rescue teams.

Figure 14. WB-57 – JSC; NASA Airborne Science Program, Ref. 62.

Figure 15 is an illustration of a notional robotic partnership between an autonomous VTOL aerial vehicle and a ground mobile robot that could be deployed from, and recovered by, the aerial vehicle to distribute aid and/or implement rescues.

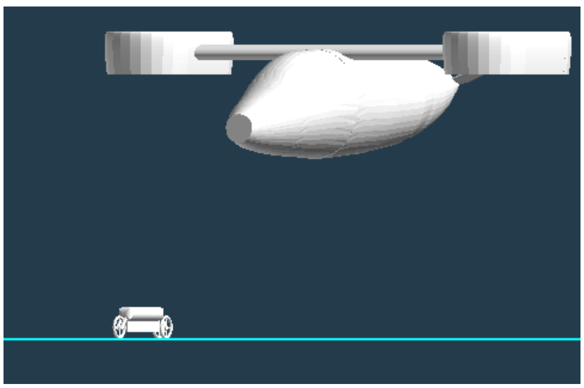

Figure 15. CAD depiction of a tilt duct air vehicle conducting a RRD rescue mission alongside a ground mobile robot.

An integrated approach to developing new rotorcraft designs and associated robotic rescue devices will be required for successful DRER missions/applications.

Safety Net

The 'Safety Net' concept is intrinsically built on the dual- or multi-use missions or use cases. Where the 'Sentinel Network' provides a hub station to provide a centralized location for emergency response, the 'Safety Net' is a concept that enables interactivity between drones and systems, and has many similar attributes as to the SPRITES network of Ref. 4 but with a stronger emphasis of drawing in non-aerial robotic systems. Some examples of interconnected drone systems include civil reserve emergency and delivery drone fleets. These types of fleets will be discussed in the context of the 'Safety Net' concept.

<u>Civil Reserve Emergency and Delivery Drone Fleet Concepts:</u>

Public/private partnerships are critical in the establishment of civil reserve emergency and delivery drone fleets. Fleets could improve accessibility of emergency response services. However, there are several considerations to be made that could help put into perspective the challenges of Safety Net implementation:

- Establishing the tradeoffs between scaling up access to emergency response aerial assets and minimizing public investment costs involves strategic planning and collaboration.
- For private aerial assets to have the ability to respond to future DRER/public-good missions, public entities would need to be part of the design discussions.
- Tradeoffs between multi-use capability, cost, and mission effectiveness.

These considerations are key in brainstorming potential harmonious solutions to disaster response. From a NASA research and technology development perspective, there could be an unexplored conceptual design 'grey area' between the current crop of industry delivery drones and the emerging urban and air mobility vehicles. Within this grey area, there is likely a spectrum of vehicle sizes, capabilities, and system-of-systems considerations that could balance both cost and effectiveness for both Sentinel Network and Safety Net concepts. Scaling up access to emergency response will require categorization of capabilities for this unexplored public good (DRER) design space, which could include:

- Emergency scouts or aerial surveyors - immediate post-disaster surveillance and communication
- 'Aid as a service' – i.e., delivery of a 5-25 lbf emergency aid package
- 'Hope/Help Delivery' - i.e., cargo from 100-300 lbf
- 'Heroes' – i.e., one to two passenger UAM vehicles (those passengers being boots-on-the ground first responders providing, for example, essential triage support
- 'Commandeered' UAM or air-taxi support (4-9 passengers for rescue, aid, and recovery)

<u>Interconnected Autonomous Aerial Vehicles, Drones, and Systems</u>

'Safety Net' is a global expansion of the above civil reserve emergency and delivery drone fleet concept. Safety Net expands the focus to non-aerial aspects of the civil reserve emergency and delivery drone fleet problem, although some considerations need to be made. One such Safety Net consideration includes automated warehouses and/or logistics centers, particularly if automated warehouses/logistics-centers can be leveraged in a public/private sense to ensure adequate supplies and distribution of those supplies during emergencies. Another consideration is whether commercial ground delivery robotic systems can also be absorbed into an integrated set of public/private partnerships to provide for targeted ground distribution in coordination with emergency/delivery drones. With these considerations in mind, the following questions should be addressed:

- Can eVTOL air-taxis and self-driving (and non-self-driving but private app-based services) cars be integrated into a DRER "Safety Net"?
- Can AI/ML, or Big Data analytics, be the glue to enable coordinated, efficient, and timely responses for the proposed civil reserve emergency and delivery drone fleets and "Safety Net"?
- What is the intersection between – and the handoff towards – going from initial emergency responses to early recovery operations?
- How can this handoff be made as efficient and effective as possible?
- How can an imbalance between DRER "Safety Net" responses in rural versus urban communities be avoided?

An example of a multi-use, multi-purpose Safety Net collaboration is shown in Figure 16, where an eVTOL rotorcraft, delivery drones, and ground delivery robots work in tandem to respond to a fire disaster scenario.

Figure 16. "Safety Net" (AI-generated image using Microsoft Copilot) eVTOL autonomous air taxis and aerial and ground delivery drones.

The proposed Sentinel Networks, Safety Net, and rotorcraft and robotic rescue devices provide the foundation for a notional system-of-systems architecture for enhanced future DRER operations. There is potential for evolvable public/private partnerships to encourage the growth and applicability of civil reserve emergency and delivery drone fleets to broader DRER missions. Further, defining the possibilities of such architecture can inspire the development of new generations of aerial and ground vehicles. A possible use case, and business case, of the strawman solution can be explored.

Consider the following scenario: an earthquake response is needed in the greater Los Angeles area. In this example, possible partners could be:

- NASA
- Industry developers of eVTOL, electric Short Takeoff and Landing (eSTOL), and electric conventional takeoff and landing vehicles (eCTOL)
- Industry drones, both aerial and ground delivery
- FAA
- State and local government

The Safety Net concept entails leveraging NASA and industry expertise and technological investments to create a comprehensive DRER architecture.

<u>Safety Net Strawman Business Case:</u>

Public/private partnerships are pursued in which emerging delivery drone efforts are further enhanced by embracing their use as emergency aid supply delivery, or aerial 'aid as a service'. Public/private partnership agreement terms should be readily scalable to reflect two ends of a spectrum of support: from routine near-daily emergency response to a major disaster response. For overall efficiency, cost-effectiveness, reliability, and scalability, striving to create a civil reserve fleet of drones and drone services (on local municipality and county-wide scales) to perform on demand emergency response (most of the time) and disaster relief missions (in rare but critical circumstances) is likely the best going forward strategy. One example of a recent public/private demonstration can be seen in Ref. 63 which examined the potential utility of in-development eVTOL vehicles in supporting DRER missions.

Private company involvement in these Safety Net efforts would be beneficial. A simple, back-of-the-envelope style analysis follows for the business case. First, it is notionally proposed that direct contract emergency service support by commercial drone companies might be supported by local governments. It is assumed that a maximum of five percent of a local government's fire department budget is potentially feasible (in the case of LA, 5% of $820M for 2024-2025 would be $41M). Such contract(s) could be for a guaranteed annual number of flights or flight time, with potential reduced rates for additional flights. Second, working towards expedited planning/permitting for logistics centers (including specialized emergency aid centers) as well as small vertiport siting to support dual-use commercial and DRER operations. Third, working towards potential expedited public hearings to address community concerns about flights in exchange for robust dual-use commercial and DRER operations.

For public organizations, there are also advantages to collaborating with private industry and government on Safety Net concepts. These are laid out as follows:

1. Increased emergency support and scalability would facilitate going from 'routine' emergencies to 'large disasters'; further, this could enable aerial 'aid as a service'.
2. Public organizations could charge $100/flight (both for flight services and emergency aid packages), which translates to about 5% of the LA fire department budget if there are ~1100 flight per day.
3. There could be potential tax reduction incentives to drone companies to establish themselves in communities by offering contracts for 'aid as a service'.

4. Local governments could potentially reduce investments into local-government-owned drones and associated DRER infrastructure.
5. There are collaborative public/private development opportunities to nurture next-generation drone designs and operational capabilities.
6. There are potentially more deliberative and holistic approaches to integrating drones and eVTOL air-taxis into local urban environments, including use of existing infrastructure to reduce infrastructure development costs.

There are additional considerations that could hinder such partnerships and system-of-system development efforts. Public organizations such as municipality governments generally struggle to define and meet their annual budgets, even for essential services such as police and fire departments; this could restrict 'discretionary' funds for civil reserve emergency and delivery drone fleets and "Safety Net" efforts. The costs of such contracts might be partially offset by reduced local-government tax incentives to drone companies in exchange for those contracts as well as agreements to expedite planning, permitting, and vetting of community viewpoints. Other contracting and collaborative agreement approaches might be feasible, including possible consideration of federal grants to initiate some public/private partnerships such as civil reserve emergency and delivery drone fleets and "Safety Net". The current generation of UAVs cannot respond to all large-scale disasters within the "golden hour", which will require aerial vehicle design and technology advancements ideally led by NASA and the larger rotorcraft research community.

THE FUTURE OF DRER MISSIONS, VEHICLES, AND NETWORKS

Rotorcraft have always been essential disaster relief and emergency response aerial vehicles. However, despite the many, many rotorcraft DRER successes, there is still a tremendous opportunity in the future to transform the DRER field with innovative aircraft, associated rescue and relief systems, and a new holistic system-of-systems perspective for missions and operations.

Innovative Mission and Vehicle Modeling Tools

One of the proposed future work efforts of VAERA is focused on improving and developing mission and vehicle modeling tools for crewed and uncrewed rotorcraft supporting DRER. Past work identified technology gaps for wildfire relief rotorcraft missions. Additionally, work has been done with rotorcraft design tools to perform vehicle sizing for different DRER missions. In Ref. 64, the design implications for Urban Air Mobility vehicles performing several public good missions are outlined. A continuation of this work, Ref. 65, goes into further detail on the VAERA wildfire missions from the vehicle design/sizing approach. In the realm of rotorcraft research, the VAERA team has been focusing on the development of mission and vehicle modeling tools as well as researching handling and flying qualities in the wildfire environment. Several concept vehicle designs have been created for a range of wildfire relief missions. Further, studies of gust characterization in wildfire conditions are underway, and potential improvements to the vehicle control system and stability for the turbulent wildfire environment are being explored, Refs. 66 and 67.

The past work and future work for VAERA involves using existing tools in new and innovative ways and, also, developing new tools. Through this work, existing tools will be validated and improved for new (and smaller) rotorcraft configurations and for extreme environments. While a lot of the work to date has been focused on wildfire relief efforts, VAERA plans to expand its focus to other DRER scenarios. There are multiple research tasks VAERA hopes to undertake.

Small drones have not proven to be able to safely and reliably operate in turbulent wildfire environments with significant payloads. With the goal of improving flight dynamics and controls, a modular drone test stand can be used to validate drones for the turbulent wildfire environment. This stand could also help assess which vehicle/rotor/blade configuration changes have the greatest effect on stability. Flight dynamics and design loops would help show which parameters have the most significant impact on mission capability and performance. Carrying out flight tests would provide flight validation of FlightCODE, described in Ref. 68, for different rotor configurations and conditions. One impact of this proposed work is that drones would be capable of delivering critical supplies directly to wildland firefighters in the field during turbulent winds from active fires.

Another proposed study outlined here, involves identification of ideal water drop locations with degraded visual environments. Traditionally, solutions rely heavily on pilot intuition and require multiple passes over the drop area to zero in on the ideal water drop point. Developing a pilot-assistance-tool software prototype specifically for wildfire suppression missions could help close the gap between water drop assistance under ideal conditions versus the realistic turbulent and degraded visual environments for wildfires. The impact of the development of pilot-assistance-tools would be that wildfires could be contained faster with more accurate water drops, decreasing both pilot workload and accidents.

The proposed future work of the VAERA effort complements the overall presented vision in this paper of an expansion of the role of vertical flight aerial vehicles in disaster relief and emergency response.

CONCLUDING REMARKS

This paper is a renewed, reenergized "call to action" for rotorcraft – and other – researchers to push the limits of engineering innovation to save lives. This paper has presented a series of thoughts related to the disaster relief and emergency response application domain for rotorcraft. DRER missions are detailed in the paper as well as discussion related to showing that rotorcraft of all types, sizes, and capabilities could have a role in DRER. Additionally, the leveraging of new fields of study, such as robotics, is also discussed and highlighted for its potential to greatly enhance the role of rotorcraft in DRER missions.

There are almost innumerable anecdotal stories of victims of disasters and emergencies of various types and magnitudes. Imagine a future in which UAVs across the Nation can be sent out within minutes of a disaster, aiding first responders, reducing risk to personnel, and saving lives. There is a lot of work to do, but if the rotorcraft community comes together to tackle this problem, it will not be that long until the community can say "help is on the way".

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