NC STATE UNIVERSITY

NASA Gateways to Blue Skies Competition
Hurricane Response

GATEWAYS TO BLUESKIES

North Carolina State University

Team REACHR

(Reconnaissance and Emergency Aircraft for Critical Hurricane Relief)

Team Members

Team Lead: Tobias Hullette
Senior
Aerospace Engineering

Sebastian Perna
Senior
Aerospace Engineering

Brian Shi
Senior
Aerospace Engineering

Jose Vizcarrondo
Senior
Aerospace Engineering

Caleb Kebede
Senior
Aerospace Engineering

Lucas Andrews
Senior
Aerospace Engineering

Faculty Advisor: Felix Ewere

North Carolina State University
Department of Mechanical and Aerospace Engineering

Contents

List of Figures

List of Tables

Abstract

Challenged by NASA's 2024 Gateways to Blue Skies: Advancing Aviation for Natural Disasters, our team has integrated cutting-edge unmanned aerial vehicle (UAV), search and rescue, and clean energy technologies into a revolutionary hurricane response system. People stranded in hurricanes and other water emergencies are often in need of basic resources such as food, safety, and shelter. There is an urgent need to identify the location of stranded individuals, provide them with communication, and deliver emergency supplies as quickly as possible. Currently, first responders attempt to find stranded individuals by helicopter or patrolling flooded streets on boats. However, in-person patrolling is inefficient and puts first responders in unnecessary danger. Our Reconnaissance Emergency Aircraft for Critical Hurricane Relief (REACHR) system aims to reduce first responder and hurricane victim risk, response operation costs, and unnecessary CO2 emissions with modern, widely untapped aviation technology. Focusing on the response phase of hurricane disaster management, the purpose of REACHR is to assist first responders in finding, communicating with, delivering supplies to, and rescuing stranded persons. The REACHR UAS will incorporate a fixed-wing unmanned aerial vehicle (UAV), designed for long endurance and capable of vertical takeoff and landing (VTOL) on water or land. The system will also make use of advanced surveillance tools such as LiDAR, FLIR, and NASA's FINDER. From acquired data, REACHR will use Artificial Intelligence (AI) for surveillance route optimization and data processing to identify stranded individuals. The UAS can then disseminate critical information to first responders using a satellite-based uplink to a web application. Additionally, the UAVs can be equipped with a payload area to carry food, water purifiers, ultralight blankets, or flotation devices. A non-profit organization will be created to facilitate the development, construction, and deployment of the REACHR system. This organization will work closely with the NCSU engineering departments on developing the system and government agencies to make sure it meets regulations. Given that most of the individual technology subsystems have already been developed to a high technology readiness level, development challenges are mostly comprised of subsystem integration. Therefore, the REACHR system is expected to be deployable by 2035, saving more lives at a lower cost and environmental risk than traditional emergency response operations.

I. Introduction

Hurricanes or tropical cyclones are naturally occurring weather systems that form over the warm waters of tropical oceans. These systems are characterized by large rotating wind patterns surrounding a low-pressure center. Hurricanes can often bring high winds greater than 100 miles per hour and rainfall of over 6 inches. However, the deadliest impact of hurricanes is often a rise in ocean water levels preceding and during the storm called a storm surge. Hurricanes often produce storm surges of over 10 feet and have been recorded to produce storm surges of over 20 feet [1]. Tropical cyclones occur most often in the mid-Atlantic and the mid-Pacific oceans. They typically travel from east to west and from south to north. This means that areas such as the Caribbean and Pacific island nations are most impacted. The most commonly affected regions in the United States are those in the Southeast such as Florida, Alabama, South Carolina, and Puerto Rico. However, tropical storms have been known to land in southern California, Arizona, and even Alaska. Hurricanes are the most costly natural disaster with damages often ranging into the hundreds of billions of dollars. For example, Hurricane Katrina in 2009 cost 196.3 billion dollars, and Hurricane Harvey in 2017 cost 156.3 billion dollars in damages [2].

In the United States, hurricanes pose the highest risk to people who live close to the Atlantic coast spanning from Texas to Delaware [3]. Mandatory and voluntary evacuation orders are often issued with the predicted landfall of major hurricanes. Hurricane Irma was no exception. However, only 54% of individuals issued a mandatory evacuation and only 37% of individuals issued a voluntary evacuation chose to evacuate. Residents such as those living in low-income communities are less likely to evacuate long distances or evacuate at all [4]. Consequently, in the event of hurricane-related floods, many people become stranded in areas with limited road access, electricity, and fresh water. There is a need to identify the location of such stranded individuals, provide them with communication, deliver emergency supplies, and plan their evacuation. In the event of a major hurricane, the president can issue a disaster declaration that mobilizes the emergency response program of the affected states and enables federal assistance [5]. At this stage, the Federal Emergency Management Agency (FEMA) coordinates disaster response through the National Response Coordination Center (NRCC). The NRCC works to coordinate information and resources across different locations, agencies, organizations, and disasters with the National Operations Center (NOC) [6]. The role of the NRCC is important since hurricane response often has to coordinate with hundreds of federal, state, and volunteer organizations. Over a dozen federal agencies such as the Coast Guard, Department of Transportation (DOT), Department of Health and Human Services (HHS), National Weather Service (NWS), Environmental Protection Agency (EPA), etc. are involved. On the state level, first responders include local fire departments, the police force, and state-wide emergency response teams. Lastly, non-government organizations such as the American Red Cross and volunteer groups are also involved. It is at this stage that aviation-related operations are most commonly implemented. States often have trained helicopter rescue teams, such as the North Carolina Helicopter-Aquatic Rescue Team, consisting of teams from the local National Guard and police patrol. Upon further escalation of flood damage and disaster scale, additional aerial support is requested on the national level such as from the Coast Guard, Army, and Navy.

Unmanned aerial system (UAS) usage in flood-related disasters has been proven to show great promise as a quick and cost-effective method of situational evaluation and disaster response. The fast deployability of unmanned aerial vehicles (UAVs) into disaster areas that are inaccessible by ground means that their biggest use case has been surveillance and mapping. For example, UAS have been used to identify road closures, building damages, flood zones, etc. Compared with manned aircraft systems, UAS offers a much lower operational cost. For example, the operational cost of search and rescue helicopters for FEMA ranges from $579/hr to $13,453/hr depending on the type of helicopter [7]. UAVs are cheaper to manufacture, they have little to no maintenance costs, and it is easier to train first responders to operate a UAS than a helicopter.

II. Use Case

Because hurricane emergency response and disaster relief operations require coordination and communication between various teams and agencies, we propose an integrated surveillance, identification, and data management system. This system features a fixed-wing, amphibious, VTOL-capable UAV and incorporates advanced technologies that enhance the efficiency and effectiveness of emergency response and disaster relief operations. The system is deployable by 2035 and can be employed in any natural disaster scenario involving flooding and/or search rescue operations.

The specific use case for REACHR's UAS is to assist in searching and rescuing stranded individuals in post-hurricane or flood conditions. The REACHR UAS is designed to conduct surveillance of flooded areas and identify stranded individuals in need of assistance. After identifying stranded individuals, the REACHR system will inform emergency responders of the location and the most efficient path to reach them. The REACHR UAS will simultaneously provide cellular coverage to all affected areas. Once individuals are identified and the required information is relayed to emergency responders, the UAV will engage with stranded individuals by landing in the water nearby, providing communication and supplies.

Given this design mission profile, the REACHR system will be indispensable in Category 1 to Category 5 hurricane response phases. With REACHR's operability in the air and on water, this system can also revolutionize disaster response operations in the case of flooding, whether it be due to a tsunami, dam break, or flash flooding thunderstorm. According to Pew, "Since 2000, at least one flood occurred in the U.S. on nearly 300 days per year, on average. The NOAA database also shows that all 50 states and the District of Columbia were affected by flooding in 2021. This ever-present risk underscores the need for comprehensive resilience planning that can help safeguard communities and the critical infrastructure they depend on daily, such as roadways, schools, and hospitals" [8]. Given this data, the REACHR system could make a significant impact by protecting hurricane and flood victims and facilitating optimized surveillance and rescue missions.

III. Design Solution Features and Expanded Definition

Based on the target use case, our team has specified several key aviation, surveillance, and data processing technologies to integrate into one UAS capable of deployment via UAVs.

A. Multi-Mode UAV

The REACHR UAS will incorporate a fleet of versatile UAVs. The various missions and modes of the REACHR require accessing difficult-to-reach areas and adverse flying conditions. With the use case and functional requirements in mind, the UAV concept design is a fixed-wing UAV with multiple flight modes including conventional takeoff and landing (CTOL), short takeoff and landing (STOL), and vertical takeoff and landing (VTOL). This allows the UAV to land and loiter in areas of dense debris, like quadrotor drones, while still maintaining the longer endurance and range of fixed-wing UAVs. The takeoff and landing mode versatility, along with water landing capabilities, expands the scope of situations in which the REACHR UAS can support hurricane response operations. The UAV capabilites are further enhanced by a modular payload. This allows room for specialized reconnaissance systems and sensors as well as medical, nutritional, or emergency supplies.

B. AI Route Planning

The AI route planning feature, powered by neural networks and Open AI, will enable the REACHR UAS to autonomously navigate and identify optimal routes for emergency response missions [9]. By analyzing real-time data and considering factors such as traffic congestion, weather conditions, and terrain, the REACHR UAS could quickly and efficiently reach the affected areas as well as direct emergency response teams to stranded individuals. The AI route planning system will improve decision-making by providing accurate and updated information to the emergency response teams while also reducing the workload required to manage the UAS. The REACHR system will incorporate an AI route planning system trained with supervised machine learning. This will require the development team to collect hurricane response and rescue data and highlight examples to anticipate and respond to a variety of mission scenarios.

C. Communications Via Web Application:

According to the 9/11 Public Discourse Project, communication during Hurricane Katrina was a classic failure of command and control as it had no unified incident reporting system to coordinate the efforts of local, state, and federal agencies [10]. To streamline the communication process between different agencies attempting to access information gathered by the REACHR UAS, a web application will be developed that greatly increases the efficiency at which data and updates are shared among first responders. Through the use of a web application, important information can clearly and efficiently be shared over a wide range of agencies without interference from other parties. This application will include features such as a map of the affected areas that highlights areas of interest, channels for communication between different agencies, as well as channels for general announcements to all agencies assisting in the operation. This application will also allow for independent communication between two parties or with stranded individuals via a two-way speaker on the UAV [11]. This could assist the psychological state of a stranded individual who is not used to emergency-induced stress.

There are numerous strategies available for creating a high-performing web application. One effective method involves utilizing an Android app developer well-versed in the Kotlin programming language to design the user interface and networking functionalities, allowing seamless communication across different devices, ranging from personal computers to smartphones. Moreover, integrating Maps SDK can enhance the application by incorporating mapping features and location-based notifications. Maps SDK, a Google Maps development tool, empowers developers to seamlessly integrate Google Maps into Android applications, offering users the ability to access functions like adding points of interest, GPS locations, and interactive map zoom capabilities. The diverse range of technologies, methods, and infrastructure required for building and running a web application is advanced and readily available, enabling us to employ a professional company or hire a freelance developer for the task.

D. Advanced Imaging

The integration of advanced imaging technologies such as LiDAR and FLIR into the REACHR UAS will enhance its surveillance and data collection capabilities.

1. LiDAR

LiDAR will enable the REACHR UAS to generate detailed 3D maps of disaster-stricken areas, providing crucial information about terrain and obstacles. This will assist in obstacle avoidance and optimizing flight and first responder rescue paths for safe and efficient operations. LiDAR systems are also capable of mapping topography underwater, identifying human forms, and plotting the most optimal route to stranded or drowning victims. The issue that arises with LiDAR is that underwater mapping requires

2. FLIR

FLIR technology will enable the REACHR UAS to detect heat signatures and visualize temperature variations, aiding in search and rescue operations and surveillance in low-light conditions [12]. AI-powered image processing will also be implemented to maximize efficiency and improve the system's ability to identify both obstacles and stranded individuals. An example of how FLIR technology could be implemented into the REACHR UAV is by purchasing off-the-shelf hardware and physically mounting it. Teledyne FLIR markets FLIR cameras compect enoughto be mounted on drones and can be used for identifying people or debris in the water at night. Mounting this camera or something similar to the front of the REACHR UAV would allow for easy identification of stranded individuals in or out of flooded regions. With its small size and low power consumption, the thermal cameras would make a great addition to REACHR's capabilities.

E. FINDER

The integration of NASA's FINDER system, soon to be commercially available through SpecOps Group, Inc., into the REACHR UAS will enable it to detect heartbeats and breaths beneath debris, rubble, or inside buildings. The commercial version of the NASA Finder, Finder MK4, has a range of 200 ft, can perform up to 150 scans per charge, and weighs 8 lbs per unit. Additionally, its ability to operate on multiple operating systems such as Windows and Linux increases its compatibility with the REACHR system. This capability is valuable in search and rescue operations, where time is of the essence. REACHR UAVs, with their aquatic capabilities, can land near structures and employ the FINDER radar technology to effectively locate potentially trapped survivors, regardless of the weather and time of day [13]. It is worth noting that FINDER will not enable REACHR to find individuals beneath the surface of the water as radar microwaves are absorbed within a few feet of their transmission in water. Besides this one shortcoming, The FINDER system will enhance the search and rescue capabilities of the REACHR UAS, increasing the chances of saving lives where other systems, such as FLIR, fail.

It is worth noting that SpecOps supplies FINDER in configurations mountable to vehicles and robots, making it a perfect candidate for REACHR's sensor suite. However, this system will need to be developed further before it becomes fully commercially available, and a viable addition to the REACHR system.

F. Solar-Enhanced Battery:

The power supply of the REACHR UAS will be supplemented by solar panels attached along the top of the UAV's wing and body to increase the duration of flight and aerial coverage. Due to the difficulty of search and rescue operations, a long flight duration may be necessary to find all stranded individuals and assist them in dangerous situations. With the increase in efficient solar power power research, it is believed that by 2035 solar-enhanced UAS will be more common and allow for longer-lasting flights. REACHR plans to put this technology to use to enhance mission endurance. To validate the concept of this technological integration, one can use a rough calculation to determine the total number of solar cells needed to power each UAV in the system [14].

$$N_T = \frac{E}{HSP \cdot Pm_{pp} \cdot n_m} \tag{1}$$

where E is the energy consumption of the UAV between charges, HSP is peak sun hours, Pm_{pp} is the max power of the panel, and n_m is the performance of the module accounting for efficiency and energy harvesting losses. The values for these variables relies heavily on the final design solution specifications including weight, lift and drag characteristics, wing area, etc.. After evaluating several different types of solar technologies and panel configurations, a monocrystalline, passivated emitter and rear contact (PERC), C60 solar cell was selected. This choice demonstrates the best balance between availability, affordability, and efficiency. To ensure that solar panels are a viable energy source for this system's UAVs, it is vital to evaluate the peak sun hours for the anticipated region of operation. Peak sun hours are characterized by solar emission of 1000 watts of power per square meter on average. This photovoltaic power distribution dictates whether solar panels are capable of effectively charging UAV batteries for frequent and unpredictable hurricane response operations. New Orleans is a frequent victim of hurricanes and flooding, so it is the reference location for deriving local photovoltaic system performance from the Photovoltaic Geographical Information System (PVGIS). For a fixed-tilt system, New Orleans has 5.0 peak sun hours per day. This is the most accurate model to use in this scenario given that the UAV will tilt and move per mission requirements, not for optimized solar charging. The fixed-tilt model gives us an accurate average HSP value to use. Overall, solar-enhanced batteries will be a viable way to power the REACHR UAVs, demonstrating the arrival of new standards for green energy in the emergency response field.

G. Aerial Signal Relay Station:

During Hurricane Katrina, massive communication damages played a role in limiting emergency responder's ability to assist stranded individuals [15]. To account for this, the payload of REACHR's UAS can be equipped with a 5G cellular relay antenna, transforming it into an aerial signal relay station. In the aftermath of a natural disaster, communication infrastructure often suffers significant damage, leaving survivors unable to call for help. By acting as a cellular relay station, REACHR's UAS will enable affected individuals to make rescue calls, facilitating faster response and assistance. Sprint has already tested this by mounting lightweight cellular radios onto UAVs which can give temporary phone coverage over as much as 10 square miles. Implementation of this technology is as simple as attaching cellular radios to the UAV but will require collaboration with phone service companies to ensure reliable coverage.

A technical challenge with this cellular relay system will be environmental conditions. "Even when a local connectivity "bubble" is provided, connectivity gaps still exist and higher [quality of service] is required at specific spots" [16]. This challenge demands a flexible system that can quickly move to correct "dead spots." The REACHR UAS can accommodate that demand with one or more secondary UAVs capable of moving in the air or on water to provide the most possible people with reliable cellular service.

Another possible solution for this challenge is using a UAV as an aerial relay node for Wi-Fi 6 between a 5G base station and on-ground users. This further diminishes connectivity gaps, eliminating interference between the UAV relay node and the base station. Wi-Fi 6 and 5G have different frequencies, allowing users to access Wi-Fi 6 without issues. This system originally proposed by Michael Batistatos, et. al. also preserves the 5G uplink, retaining URLLC (Ultra-Reliable and Low Latency Communications), eMBB (Enhanced Mobile Broadband), and mMTC (Massive Machine-Type Communications) [16]. The REACHR UAS is a perfect candidate to integrate this cellular relay system architecture and provide hurricane responders with a reliable Wi-Fi signal.

H. Satellite-Based Data Uplink:

In the case of widespread power outages, the most reliable form of internet access may be obtained through satellite-based providers such as Starlink or Viasat. Through an antenna unit attached to the UAV, fast and reliable data transmission can be secured throughout the mission plane regardless of the severity of damage to the existing internet infrastructure. Another possible implementation of such a system could be through the utilization of short-burst data (SBD) transmissions that can be facilitated by lightweight and low-power modules. With SBD, basic information such as survivor location and condition can be relayed to operation centers regardless of the presence of ground-based internet. SBD transmissions also offer the advantage of requiring smaller, lighter, and cheaper modules.

I. Equipment Suite Specifications

The table below, Tab. 1 shows a quick overview of the technical details for the sensors and components we have specified to equip the REACHR UAS. "N/A" signifies that the component has an onboard chargeable battery.

Table 1 Notable System Modules and Per Unit Characteristics

Component	Vendor	Size	Weight	Cost	Power Usage
FLIR VUE Pro 640 [12]	Teledyne FLIR	2.26 x 1.75 in	4 oz	$3,895.00	2.1 W
FINDER MK4 [13]	SpecOps Group	22 x 14 x 9 in	8.3 lb	not available	N/A
C60 Solar Cell [17]	Full Battery	5 x 5 in	0.23 oz	$3.00	3.6W
5G / Wi-Fi 6 Hotspot [18]	NETGEAR	4.14 x 4.14 x 0.85 in	0.56lb	$1054.00	N/A
SkyLink 7100 [19]	Skytrac	5 x 8 x 1.25 in	1.6 lbs	$3500.00	7 W
RockBLOCK 9603 [20]	Ground Control	1.78 x 1.78 x 0.59 in	1.27 oz	$280.00	0.45 W

IV. System Integration and Expanded Analysis

A. System Integration:

Below is a conceptual block diagram illustrating interactions of the various technologies and subsystems outlined above.

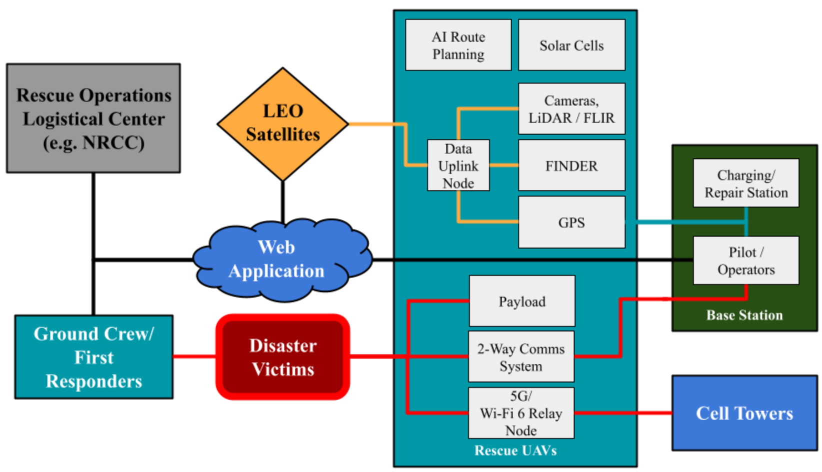

Fig. 1 Conceptual Block Diagram

What Fig. 1 doesn't explicitly outline is the division of technology and sensor equipment for a fleet of UAV's. For example, the realized system may have different UAVs dedicated to survivor identification with the NASA FINDER while others are dedicated to payload delivery and survivor communication.

B. UAV Initial Sizing Analysis

Based on the payload, mission, and regulatory requirements, it is possible to estimate the weight and power requirements of the REACHR UAV. This step is important for analyzing the feasibility of the manufacturing and operation of the UAV which plays a central role in the overall hurricane response system.

1. Weight Requirements

The UAV needs to have a payload capacity of at least 8.3 lbs in order to carry the NASA Finder. Additionally, it still needs to be able to house all the other necessary avionics and sensor systems such as the flight computer, batteries, and satellite transmitters. Finally, to simplify the legal process of operating the UAV, the overall weight of the UAV needs to stay below 55 lbs in order to be classified as a "medium-sized" UAV. Above this weight limit, large UAVs have higher flight ceilings and speed limits that make them subject to additional regulations, making the operation of such vehicles significantly more complex. Taking these considerations into mind, the UAV will likely be around 40-45 lbs empty with around 10 lbs of payload for either survivor rescue supplies or the NASA Finder.

A prototype (below) presents a possible design configuration that meets the outlined weight requirements. Note that the prototype is an approximately 50% scale (by weight) version of the production full-scale UAV.

2. Power Requirements

Given that the operating time is one of the critical limiting factors in a UAV's practicality, it is important to characterize the power requirements of various systems and the corresponding power bank needed to achieve meaningful flight endurance. Notably, the NASA Finder has its battery built into the unit. Therefore, given the size of the aircraft, the power requirements of avionics and subsystems are likely small compared to the power requirements of the propulsion system.

Without the exact configuration of the UAV it is impossible to determine the precise power consumption of the propulsion system. However, based on general rules of thumb for RC planes and multicopters, the power-to-weight ratio of a VTOL-capable fixed-wing UAV would range between 50 W in level forward flight to 200 in maximum thrust VTOL maneuvers [21]. Assuming the maximum possible take-off weight of 55 lbs, the power from the propulsion ranges from 2750 W to 11000 W. This includes motor and propeller combinations powered by batteries connected with ESCs. All other electronics have very minimal wattage values in comparison to propulsion, accounting for contributions from the solar cells. This indicates that the majority of power consumption will come from the propulsion system, mainly through expenditure while in VTOL mode.

C. Prototype and Testing:

The cornerstone component of this system is the UAV that houses all the sensors and technologies Team REACHR has specified for its mission. So, having designed a concept for a state-of-the-art UAS, Team REACHR decided to further prove the concept by prototyping a UAV as a platform with which to integrate all the proposed technologies into one system. Team REACHR restricted the entire design, build, and test phase to a total budget of $1500.00. Sizing was also an important constraint when decided strategically early. The prototype was designed to fit within a standard car trunk (5ft x 3ft x 2ft) when disassembled to simplify transportation and facilitate frequent system and flight tests. The computer-aided design render in Fig. 2 shows the completed design model, drawn in SolidWorks.

Fig. 2 HERO 1 Vehicle Design Concept

The vehicle concept design for the REACHR system UAV, HERO 1 (Hurricane and Emergency Response Operative) is a product of an extensive literature review, trade studies, verification, validation, testing, and iterative design. Given the budget and size constraints, HERO 1 is designed to be as versatile and capable as possible, integrating strong, lightweight materials, optimized subsystem and component design, and maximized payload capacity. HERO 1 is a fixed-wing UAV with multiple flight modes including conventional takeoff and landing (CTOL), short takeoff and landing (STOL), and vertical takeoff and landing (VTOL). This allows the UAV to land and loiter in areas of dense debris, like quadrotor drones, while still maintaining the longer endurance and range of fixed-wing UAVs. The takeoff and landing mode versatility, along with water landing capabilities, expands the scope of situations in which the REACHR UAS can support hurricane response operations.

To prove the concept of a multi-mode UAV capable of outfitting the REACHR UAS, Team REACHR tested HERO 1 in three main operational modes: VTOL, cruise flight, and water operations. HERO 1's success in each of these areas demonstrated the possibility of deploying an autonomous UAV that can take off vertically from crowded or flooded areas, transition to cruise flight for efficient and quick arrival, and land on water, operating as a boat to provide survivors with communication and supplies. HERO 1 underwent VTOL testing first. The main challenges involved flight controller tuning, pilot input, and tilt-rotor controls.

Fig. 3 VTOL on Water

This VTOL flight testing, shown in Fig 3, proved that HERO 1 is capable of performing VTOL operations, making the REACHR UAS deployable from remote or urban areas without a runway. The REACHR UAS can have a much wider reach if its UAV is efficient and quick in long-range operations. This requirement demands that the VTOL UAV is also capable of cruise flight. As shown in the design solution, the front two motors are mounted on a tilting spar that rotates forward 45 degrees to initiate forward motion, by which the wings create lift. The motors then rotate a full 90 degrees forward, fully transitioning HERO 1 from tricopter hover flight to fixed-wing cruise flight. This flight mode transition is difficult from both a structural and control and stability standpoint. To improve chances of success, the pilot first hovered HERO 1 to an altitude of about 50 ft, at which point he initiated the cruise transition. Below are some images from the cruise flight test. This operational flight test proves the possibility of deploying the REACHR UAS quickly in long-range and endurance missions. Given that HERO 1 is a hurricane response operative, it was crucial to demonstrate its effectiveness in water takeoff, landing, and maneuverability capabilities. This operational mode comes with its own set of challenges, including waterproofing the UAV, properly tuning the center of buoyancy, and ensuring the motors and tilt-rotors have water-level clearance to operate.

This operational test verified that HERO 1 can take off and land on water, as well as maneuver like a boat on the surface, enabling the REACHR system to reach stranded individuals even in urban or rural areas flooded and otherwise unreachable.

V. Conceptualization of Implementation

A. Concept of Operations:

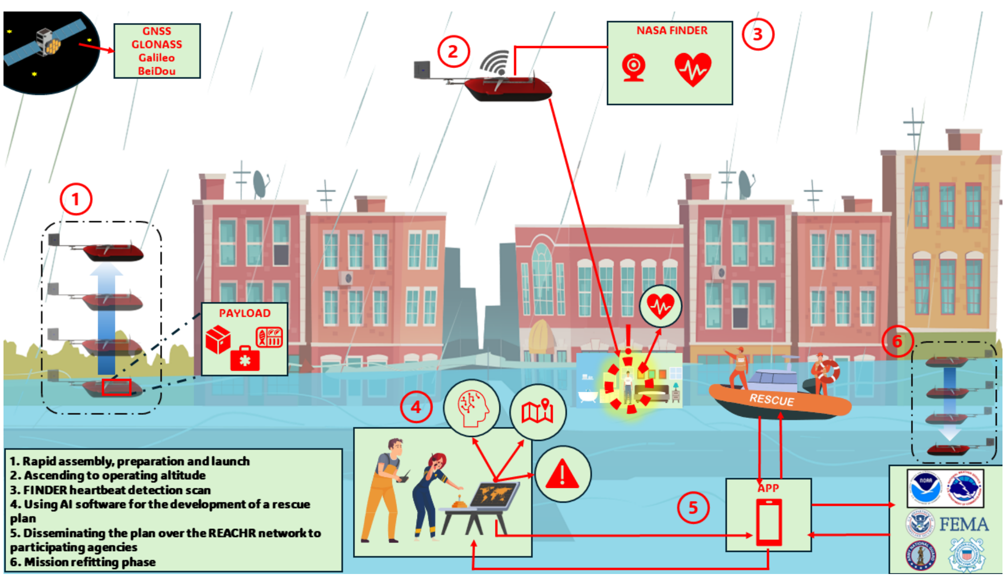

Fig. 4 CONOPS Diagram

The concept of operations (CONOPS) diagram, shown in Fig. 4, outlines post-hurricane rescue response with the REACHR system and integrates various stages to maximize operational efficiency.

The process begins with the rapid assembly and launch of the REACHR UAS, operated remotely by the pilot in command with support from an observer. The UAV can be launched by water and fitted with the required mission payload. As the UAS ascends to its operating altitude, it deploys sensor systems to gather situational data about the affected area. The UAS is equipped with advanced avionics, including surveillance tools, object recognition, and GPS tracking. The collected data is wirelessly transmitted to the ground crew via satellite uplinks. Using artificial intelligence software, the ground crew processes the data to develop a rapid rescue plan. The software can analyze the data from the UAS's sensor systems to assess the number of victims and their condition. Additionally, the software generates a rescue route avoiding any detected hazards, increasing the safety of rescue crews, and reducing the response time. Relevant data can then be managed by teams working with the NRCC and distributed across rescue agencies and organizations through a web application.

B. Major Considerations:

1. Minimal barriers to adoption/use:

Although many first responders may initially be skeptical of new technology, the implementation of AI route planning into the REACHR system will improve effectiveness and minimize the need for human input. This feature will also be able to factor in the range and endurance of the aircraft to make the best use of time and reduce the likelihood of the aircraft being stranded in the field due to power loss. The system will aim to be as user-friendly as possible through modularity in both the payload and power supply. Though training will be necessary, the REACHR system is designed to operate with as little or as much input as the user requires. Input from a diverse group of first responders will help the design team turn this concept and preliminary design into an effective and usable system.

2. Cost and return on investment:

One of the most expensive phases of natural disasters, hurricanes especially, is the recovery phase. Although the REACHR system is focused on the response phase, the studies conducted by the system during the response phase will be used to ensure a more efficient recovery phase. The REACHR system will implement expensive surveying technology (LiDAR, FLIR, FINDER, etc.), however, the system will minimize maintenance and operation costs. Time and resources that are currently wasted to plan hurricane response with highly variable trial and error will be greatly reduced with the REACHR UAS. Once in the field, the lives saved and recovery planning assistance will provide an irrefutable return on investment. Some direct cost comparisons can be made between the cost of operating a UAV versus small surveillance helicopters with similar roles. While helicopters have hourly operational costs of $600 to $800, UAVs have almost no associated operational costs. At the same time, the acquisition cost of small helicopters such as the Bell-206 often ranges over $500,000 compared to medium-sized UAVs which can be acquired for less than $10,000 [7]. This means that hundreds of thousands of dollars can be saved per hurricane response operation with the REACHR UAS.

3. Support system requirements:

The REACHR system will require a support computer to be connected to and used for data analysis. Other support systems may include a team to launch the system and a pilot to remote control the aircraft, however, this will only be necessary if the AI route planning and autopilot guidance systems are offline. Additional support infrastructure is necessary to facilitate the data collection and distribution system such as server hosting hardware, however, these systems are largely already in place.

4. Connectivity constraints:

The real-time audio and visual communication provided by the REACHR system will likely have connectivity constraints due to impacts of both weather and range. However, when data cannot be transmitted in real-time, the REACHR system will still be able to store data and return to the launch location for direct data transmission. To reduce the likelihood of issues with power access, the REACHR system will implement solar cells along with rechargeable batteries that are easily exchangeable. Upon landing, an operator should be able to exchange the battery/batteries for a fully charged set and return to flying within a few minutes rather than possibly being out of commission for hours until the battery is fully charged.

5. Challenges posed by adverse environmental conditions:

During the response phase of a hurricane, the main environmental concerns will be rain and wind. UAVs within the REACHR system will be waterproofed for water landing/takeoff and also to protect the internal components from rain. The use of both LiDAR and FLIR will ensure that the surveillance is still effective when natural visibility is low. Both the signal relaying and solar cells will be impeded by weather conditions such as rain and cloudiness. Although the weather may reduce the effectiveness of the solar panel technology, the exchangeable batteries will ensure that the system has the maximum amount of air time possible. Concerning the aerial signal relaying, the weather will only reduce the performance slightly. Wind will be a concern in terms of the aerodynamic stability and control of the aircraft. VTOL capabilities will mitigate the possible issues due to wind during takeoff and landing. Although the REACHR UAS may not be safe to fly in the most extreme hurricane conditions, the system will still gain access to debris and flood-restricted areas much sooner than manned response teams by being autonomous and through the deployment of multiple units.

6. Interoperability with existing people, processes, organizations, solutions, and technologies:

Currently, interoperation coordination is primarily conducted through the use of handheld and ground-based two-way radio systems. However, this method of coordination becomes ineffective in situations such as natural disasters or complex operations, as multiple individuals or teams are trying to disseminate information simultaneously, leading to congested radio lines, misinformation, and confusion. Our proposal suggests the implementation of a UAS with advanced AI capabilities. UAVs within the system will be equipped to transmit reconnaissance data to a ground station for processing. The processed data will include optimized rescue plans, complete with rescue routes, maps, and highlighted hazards and points of interest. The processed data will be readily accessible to all team members and participating agencies through a user-friendly digital web-based application. This application will provide real-time updates and enable agencies to make specific requests for information from the REACHR UAS crew. Lastly, within the proposed interoperability framework, all participating members will have the ability to contribute to the overall situational awareness by providing status updates on their progress or by issuing warnings and advisories to other agencies. This feature will facilitate real-time information sharing and allow for a comprehensive understanding of the evolving situation.

7. Expected improvement over existing practices:

The largest improvement that the REACHR UAS will bring is in the time of response. Many search and rescue operations within current systems are limited in how quickly they can respond due to flooding, weather, and other obstacles. The REACHR UAS will gain access to the entire disaster-stricken area as soon as wind speeds slow to a reasonable level. LiDAR, FLIR, and FINDER will give vision into areas inaccessible to search and rescue teams. This will help with response time and direct responders and resources to the most urgent areas of concern. This optimized response system will also improve costs, minimizing infrastructure damage, first responder pay time, and full-size vehicle operation.

VI. Path to Deployment

A key benefit of the REACHR system is its straightforward plan of implementation by 2035. This plan includes all stages of ideation and development through manufacturing, approval, and eventual distribution. Currently, the Technical Readiness Level (TRL) of the actual REACHR system is 4, being a formulated concept with a proposed application and preliminary proof of concept flight capabilities demonstrated. However, most of its equipment subsystems are at a TRL of 8, being flight-qualified [22]. The challenge of the REACHR development is integrating all the technologically ready components and subsystems into one complete flight-ready system capable of improving hurricane and flood response measures. The most challenging features to implement will be the AI route planning and FINDER systems. They are still under development for projects under different contexts and will require significant time and resource commitment to apply to unmanned aerial hurricane response vehicles in the REACHR fleet. Training, approvals, and regulation adherence validation comprise another significant portion of the REACHR system implementation timeline allocation.

The REACHR system will be facilitated by the creation of a non-profit organization. The creation of this organization will centralize the management of the development and implementation of the system. This also allows for the employment of engineering teams to build UAS and flight operators.

REACHR's implementation plan is divided into four main tracks: Design and Manufacturing, Customer Operations, Field Operations, and Policy and Regulations. The timeline starts in 2024 with a preliminary design. Our team will design and deliver a preliminary system and subsequent vehicle design for NASA's Gateways to Blue Skies competition. This effort will be facilitated by NC State research faculty and students. In the Mechanical and Aerospace Department, we will seek design optimization and manufacturing expertise from the Composites Design and Manufacturing Laboratory and Computational Mechanics and Simulation System Design Optimization Laboratory. The Department of Natural Resources at NC State would aid team REACHR in developing a hurricane response system that implements the latest response methods and technologies. The Department of Natural Resources could connect us with resources and contacts with FEMA to ensure the system design solution aligns with specific needs and missions. Upon customer approval, the preliminary system design will be tailored to fit the requirements of a specific field of operation. Coastal fire departments and first responder units could offer insight as the system is tuned and tailored.

Once the critical system and vehicle designs are approved, prototyping and testing can begin in parallel with field testing and barrier analysis. The barrier analysis phase will include identifying current and potential hazards to the project and developing barriers of hazard protection in case of project failure. These phases could be completed by the end of 2028.

The customer or other operative stakeholders, such as emergency medical technicians, firefighters, and other first responders will be trained on the system with simulators and best practices, during which systems will be integrated. Field training can begin alongside risk mitigation, given tests and training data from the field. These stages will be followed by the final design and manufacturing and should be mostly completed by the end of 2031. At this point, policy and regulation adherence can be verified and approved, the UAVs can be distributed, and the system can be integrated into hurricane response teams across the world. Team REACHR expects the conceptualized system to be completely implemented by 2035.

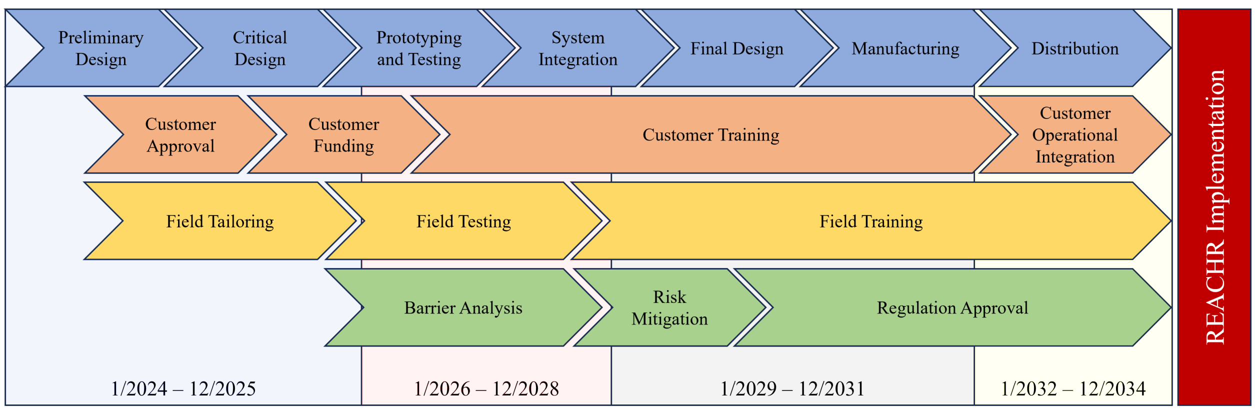

Fig. 5 Path to Deployment

VII. Conclusion and Key Findings

Our team has extensively researched the need for and physically demonstrated the feasibility of the REACHR UAS. This process has revealed several key findings critical to the development and deployment of a revolutionary aerial hurricane response system. First of all, there is a desperate need for a quickly deployable, multi-mode UAV, capable of finding hurricane and flood victims, and providing them with supplies, internet, and communication. This will greatly reduce hurricane response time, cost, and risk. There are also several aspects of this UAS design that will require technological development to define, such as sensor and equipment integration. However, our team has proven the concept of a multi-mode UAV capable of VTOL operations on land or water with long-range, low-power cruise flight for a wider system reach. We found that a UAV such as HERO 1 comes with a set of design challenges such as power requirements, waterproofing, buoyancy tuning, and ensuring water-level clearance for moving and sensing components. Lastly, considering the current TRL for concept components and various barriers to adoption, we are confident that the REACHR UAS can be developed, tested, implemented, and deployed by 2035. We have done a comprehensive analysis of design challenges, component readiness, possible challenges, and access to supporting research, development, and manufacturing teams, forming a rough but realistic timeline for implementation.

The REACHR system is no longer an idea. It is a proven concept, ready for further development and first-of-its-kind fieldwork in the aftermath of hurricanes and floods throughout the United States and around the world.

References

[1] “Storm surge overview,” Retrieved from https://www.nhc.noaa.gov/surge/, 2023.

[2] NOAA, “Hurricane Costs,” , 2024. URL https://coast.noaa.gov/states/fast-facts/hurricane-costs.html.

[3] “Hurricane,” Retrieved from https://hazards.fema.gov/nri/hurricane, 2023.

[4] Younes, H., Darzi, A., and Zhang, L., “How effective are evacuation orders? An analysis of decision making among vulnerable populations in Florida during hurricane Irma,” *Travel Behaviour and Society*, Vol. 25, 2021, p. 144–152. https://doi.org/10.1016/j.tbs.2021.07.006, URL http://dx.doi.org/10.1016/j.tbs.2021.07.006.

[5] “A guide to the disaster declaration process and federal disaster assistance,” Retrieved from https://www.fema.gov/pdf/rrr/dec_proc.pdf, 2023.

[6] “National incident support manual,” Retrieved from https://www.fema.gov/pdf/rrr/dec_proc.pdf, 2013.

[7] “Schedule of equipment rates,” Retrieved from https://www.fema.gov/assistance/public/tools-resources/schedule-equipment-rates, 2023.

[8] Tompkins, F., and Watts, B., “Flooding Is Nearly a Daily Occurrence Throughout the U.S.” 2022. URL https://www.pewtrusts.org/en/research-and-analysis/articles/2022/12/15/flooding-is-nearly-a-daily-occurrence-throughout-the-us#:~:text=Since%202000%2C%20at%20least%20one,affected%20by%20flooding%20in%202021.

[9] P, S. R., Gudla, R., Telidevulapalli, V. S., Kota, J. S., and Mandha, G., “Review on self-driving cars using neural network architectures,” *World Journal of Advanced Research and Reviews*, 2022.

[10] AFCEA, “Hurricane Katrina represents a failure to communicate,” Retrieved from https://www.afcea.org/signal-media/hurricane-katrina-represents-failure-communicate, 2005.

[11] “UAV megaphone and drone speaker for real-time speaking broadcast and SD card audio file display,” Retrieved from https://www.hk-ifly.com/UAV-Megaphone-and-Drone-Speaker-for-Real-time-Speaking-broadcast-and-SD-Card-audio-file-display-pd44289696.html, 2023.

[12] “FLIR Vue Pro,” Retrieved from https://www.flir.com/products/vue-pro/?vertical=suas&segment=oem, 2023.

[13] “FINDER finds its way into rescuers’ toolkits,” Retrieved from https://spinoff.nasa.gov/FINDER-Finds-Its-Way-into-Rescuers-Toolkits, 2023.

[14] Salazar, F., Martinez-Garcia, M. S., de Castro, A., Logroño, N., Cazorla-Logroño, M. F., Guamán-Molina, J., and Gómez, C., “Optimization of the solar energy storage capacity for a monitoring UAV,” *Sustainable Futures*, Vol. 7, 2024, p. 100146. https://doi.org/https://doi.org/10.1016/j.sftr.2023.100146, URL https://www.sciencedirect.com/science/article/pii/S2666188823000424.

[15] Leitl, E., “In Critical Care,” Vol. 10, No. 1, 2006, p. 110. https://doi.org/10.1186/cc3945.

[16] Batistatos, M., Kourtis, M.-A., Xilouris, G., Santorinaios, D., Oikonomakis, A., Bozis, E.-Z., and Kourtis, A., “Wi-Fi 6 aerial relay node in 5G network for emergency operations,” *AEU - International Journal of Electronics and Communications*, Vol. 170, 2023, p. 154776. https://doi.org/https://doi.org/10.1016/j.aeue.2023.154776, URL https://www.sciencedirect.com/science/article/pii/S1434841123002509.

[17] “Solar Cells,” Retrieved from https://fullbattery.com/collections/solar-panels/products/sunpower-c60-solar-cell, 2024.

[18] “Nighthawk M6 Pro 5G mmWave WiFi 6E Mobile Hotspot Router, Unlocked, up to 8Gbps,” Retrieved from https://www.netgear.com/home/mobile-wifi/hotspots/mr6550/?gad_source=1&gclid=CjwKCAjw0YGyBhByEiwAQmBEWgEQZYFCScWC_yXrbCLrhlpJYR11ziUTJpGP0lIdPhebDU8rHdIlIBoCKtEQAvD_BwE, 2024.

[19] “SkyLink-7100,” Retrieved from https://blueskynetwork.com/products/skylink-7100/?utm_term=&utm_campaign=BSN-Brand-Leads-Performance+Max&utm_source=adwords&utm_medium=ppc&hsa_acc=7762715551&hsa_cam=20733462386&hsa_grp=&hsa_ad=&hsa_src=x&hsa_tgt=&hsa_kw=&hsa_mt=&hsa_net=adwords&hsa_ver=3&gad_source=1&gclid=CjwKCAjw0YGyBhByEiwAQmBEWln7UfwUq1c0owr4pAg0bxou26rIu_oOlUNb26tNNM3o_eIzMF04bxoC_5gQAvD_BwE, 2024.

[20] “RockBLOCK 9603,” Retrieved from https://www.groundcontrol.com/product/rockblock-9603-compact-plug-and-play-satellite-transmitter/, 2024.

[21] “The Watts Per Pound Rule,” Retrieved from https://www.rc-airplane-world.com/watts-per-pound.html, 2022.

[22] Manning, C. G., N. ., “Technology readiness levels,” Retrieved from https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/, 2023.