Aircraft Design Implications for Urban Air Mobility Vehicles Performing Public Good Missions

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ABSTRACT

NASA has previously designed and described set of concept aircraft to serve as reference vehicles for Urban Air Mobility (UAM), to encourage public discussion and research. These vehicles are used in this paper to quantify how suitable UAM aircraft might be for missions other than their primary commercial design missions. A set of representative public good missions are described, along with design requirements and equipage. For two of these missions, the additional weight, power, and cost to facilitate a basic vehicle which may be built or configured with the ability to perform these missions is quantified. Special layout and other considerations which may impact vehicle design are described. For aircraft designed to the NASA UAM reference mission, the addition of some meaningful public good missions causes less than 10% growth in weight and power for fossil-fueled aircraft; advanced battery-electric powered aircraft grow by a significantly larger amount and may only be possible with relaxed requirements. Meaningful public good missions with UAM vehicles are feasible, provided that public good mission requirements are considered and incorporated in the conceptual design stage of development.

INTRODUCTION

Whether Urban Air Mobility (UAM) eventually becomes a widespread aircraft market or not, there will be emergencies and disasters that impact people's lives. Due to widespread disruption of infrastructure in such times, vertical takeoff and landing aircraft (VTOLs) are often the only practical vehicles to perform some critical service missions. In times of crisis, there is not enough time to design, build, and deploy a fleet of aircraft and train operators to serve the public, requiring either purpose-built or repurposed existing vehicles to be pressed into service.

Other, more mundane and even routine activities may also be performed by aircraft in the service of public good. Some of these activities are performed today by helicopters and uninhabited aircraft and might conceivably be performed by UAM aircraft in the future.

If history is a guide, the cost of developing, deploying, and operating a single-purpose aircraft for emergency or other public good operations will be viewed as too prohibitive, and thus vehicles which perform public good missions will do so in a secondary role or as a variant aircraft in a larger production run. In addition to these configured-at-delivery variant aircraft, military and parapublic helicopters and tiltrotors may pressed into service to fill these needs, and indeed perform valuable missions in emergencies. Fixed wing vehicles are used for some of these missions in the United States as part of the Civil Air Patrol, an auxiliary of the United States Air Force. As UAM aircraft come into service, the authors expect that the UAM fleet will be similarly pressed into service during emergencies. The Transformative Vertical Flight Initiative (TVF) has Working Group #4, "Public Services," specifically looking at these kinds of public good missions and has prepared an extensive a white paper outlining the results of their work (Ref. 1). NASA has contracted with Deloitte Consulting, LLP to similarly identify opportunities in the public good realm, with the result being a report that arrived at similar conclusions to those of TVF Working Group #4 (Ref. 2). Some aircraft developers, such as EHang with its firefighting kit for the 216 aircraft (Ref. 3), have proposed making secondary use of their aircraft in public good roles, and some have proposed a primary role, such as Jump Aero's aircraft to ferry first responders to the scene of an emergency (Ref. 4). If large fleets of commercial UAM vehicles will exist in and around a city that may experience a disaster, then it is prudent to predict opportunities to contribute in order to establish required capabilities and procedures beforehand.

Several important aspects remain unknown for UAM vehicles, including what capabilities these vehicles will realistically have for off-design applications, and what are the costs of designing the vehicles to have meaningful capabilities for public good missions. The NASA UAM Reference Vehicles may be used to quantify typical capabilities in off-design applications and the cost of trades to improve capabilities. Some of the previously-designed NASA UAM Reference Vehicles are shown below: multiple single occupant 4-rotor multirotors (MR), 6 occupant side-by-side helicopters (SbS, Figure 1 for an example), and 15 occupant

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Presented at the Vertical Flight Society's 80th Annual Forum & Technology Display, Montréal, Québec, Canada, May 7-9, 2024.

tiltwings (TW) were presented at the AHS San Francisco Technical Meeting in 2018 (Ref. 5); 6 occupant SbS helicopters, 6 occupant MR vehicles (Figure 2), and 6 occupant lift+cruise (LpC, Figure 3) aircraft were presented later in 2018 at AIAA AVIATION in Atlanta (Ref. 6); quiet single main rotor helicopters (QSMR, Figure 4) were presented at the 2020 VFS San Jose Technical Meeting (Ref. 7); 6 occupant Tiltwings (Figure 5) were described in a 2021 NASA Technical Memorandum (Ref. 8); 6 occupant high efficiency civil tiltrotors (HECTR, Figure 6) were presented at the VFS Technical Meeting in San Jose (Ref. 9).

Figure 1. Side-by-side helicopter (SbS), turboshaft

Figure 2. Quadrotor (4-rotor multirotor MR), turboshaft

Figure 3. Lift+cruise compound (LpC), turboelectric

Figure 4. Quiet single main rotor helicopter (QSMR)

Figure 5. Tiltwing (TW), turboelectric

Figure 6. High efficiency civil tiltrotor (HECTR), turboshaft

Table 1 is organized by increasing number of rotors from the quiet single main rotor helicopter with one main rotor and a NOTAR tail to the lift+cruise aircraft with 8 lifting rotors and one cruise rotor. The table presents disk loading (primary UAM mission design gross weight divided by the sum of non-overlapping lifting rotor disk area), which broadly indicates the approximate hover efficiency of a vehicle (lower disk loading more efficient in general), and the expected downwash velocity below the vehicle (lower disk loading lower speed downwash). Disk loading varies from a low of 3.5 lb/ft^2 to as high as 20 lb/ft^2, which encompasses nearly the entire range of disk loadings which are present in fielded rotorcraft today, allowing us to make analogies to the downwash characteristics of these vehicles. The table also identifies some different propulsion system approaches that had been designed for excursions from the baseline vehicles. In particular, fossil fuel powered and battery powered aircraft are interesting comparisons, as we expect fossil fuel powered aircraft to show less sensitivity than battery powered aircraft to additional stressing requirements on mission equipment weight, installed power, range, and endurance.

Table 1. Sources for information on NASA UAM Reference Vehicles

Type	QSMR	SbS	HECTR	MR	TW	LpC
References	7	5; 6	9	5; 6	5; 8	6
# of rotors	1+1	2	2	4	4; 8	8+1
Disk load[a]	4.0	5.0	12	3.5	20	13[b]
(lb/ft^2)		3.5	10	3.0		13
Occupants	6	6	6	1, 6	15, 6	6
Turboshaft	●	●	●	●	●	
Hybrid		●		●	●	●
Battery		●	●	●		●
Diesel				●		
AvGas				●		

[a] Turboshaft or hybrid first line, battery second (weight/area)

[b] Turboelectric resized in 2021 with updated technology

Thus far, the public discussion of using UAM aircraft for public good has not included quantitative assessment of the required equipment nor the sensitivities of vehicles to imposition of new requirements; this paper seeks to begin quantitative analysis and provide information to benefit community discussions.

The design space and number of possible permutations of vehicles and public good missions are too large to consider in this paper. A subset of possible public good missions and a subset of the vehicles in those missions are presented for discussing trends and special considerations.

UAM VEHICLE DESIGN METHODOLOGY

The UAM reference vehicles developed by NASA had been originally designed to meet a commercial passenger transport UAM sizing mission (Ref. 10), with 6 occupants flown for 2 flights of 37.5 nm (69.45 km) each before refueling or recharging. In these initial studies, the front seats were for a passenger and an unspecified pilot or passenger, with the pilot's flight control allocation being replaced by sensors and processing avionics if the vehicle were to be flown without onboard crew. More recent work inside of NASA has considered a 5 occupant cabin, where one occupant is explicitly a pilot in command, with a flight profile as shown in Figure 16. This 5 occupant mission is more indicative of present industry trends, and has the benefit of significantly reducing the size of battery electric powered vehicles, especially when considering current battery technology. For this study, only advanced battery technology is considered, with 500 Wh/kg rated capacity cells and 340 Wh/kg usable at the pack level.

The vehicles for the present study have been designed using the conceptual design toolchain described in Ref. 11. The majority of the execution for the design and off-design activities of the present study have been performed using the NASA Design and Analysis of Rotorcraft software (NDARC, Ref. 12) and OpenVSP (Ref. 13). NDARC provides simple mechanisms to add/subtract weight and drag increments and calculate mission capability given either constrained capability or for an aircraft which is sized to a set of requirements. OpenVSP allows rapid generation of parametric geometry specific to aircraft, with the ability to place internal and external components and calculate rough inertia properties.

One aspect of the designs for UAM missions which has ramifications for vehicle utility in public good missions is the design of the fuselage. The cabin is configured for passenger transport, with a pilot/operator in the front right seat, with a baggage compartment located alongside. Figure 7 shows an illustration of the segments of the UAM quadrotor fuselage, as viewed from above. The general layout of the cabin has been applied to each of the UAM reference vehicles. The four passenger seats are located in two rows of two seats, with large doors on either side for easy ingress and egress, with passenger access from the sides. Large windows provide a large field of view to the sides of the vehicle. The seating layout in these vehicles is focused on passenger comfort and efficiency of loading and unloading.

Figure 7. Top view of 5 occupant quadrotor cabin layout

Figure 8 depicts passengers exiting the UAM quadrotor after a flight. The rotors, wings, and other protrusions in the UAM reference vehicles have been placed high and away from the sides of the vehicles when possible. Note large side doors open upward for a clear path and to provide some shelter from precipitation. There are two fixed vertical support beams at the front on both side of the passenger seating area which do not move with the door. These support beams are aft of the pilot and baggage, and reduce the unsupported span of the openings. The vertical support beams at the forward and aft ends of the opening are substantial structures, and necessary to provide an unyielding load path to the cabin ceiling in the event of a crash. The need for these vertical support structures has been made clear by recent analysis and crash testing of a full-scale fuselage section representing an early version of the UAM lift+cruise cabin. During that test, the engineered sub-floor and seats mitigated the initial impact loads to a survivable level, but the vertical supports failed, and the large mass mounted to the top of the fuselage caused the roof to deform into the cabin space, resulting in an un-survivable crash event for some of the occupants (Ref. 14).

Figure 8. Illustration of passengers departing a UAM flight

The layout of the UAM tiltwing vehicle demonstrates a different set of challenges and an approach to providing convenience and comfort to UAM passengers, as depicted in Figure 9. The tilt of the wing for takeoff and landing in helicopter/conversion mode results in the wing trailing edge being near the door openings on the sides of the vehicle, precluding upward swinging doors as seen in the quadrotor. The sweep of the wing results in the wing trailing edge getting lower as it gets further from the cabin. If the wing is instead rotated to airplane mode on the ground, the path from the doors is cleared, but the rotors are located near passengers, and require the passengers to move almost directly to the rear of the aircraft. Because the aircraft has electric motors, the rotors may be stopped on the ground, so the risk to personnel from rotor strike is less than for traditional rotorcraft with turning rotors. A turboelectric aircraft would likely have exhaust toward the aft of the fuselage, and it is not likely that the turboshaft would be stopped on the ground, thus exhaust and noise should be considered as additional reasons to keep the passengers toward the front of the vehicle. To address these concerns, a partial tilt of the wing on the ground is a good compromise, as it keeps the wing trailing edge and rotors away from passengers, and provides good access to the sides and front of the vehicle.

Figure 9. Tiltwing on the ground with passengers nearby

Baseline vehicles, Excursions, Variants, and Mission Configurations

The baseline vehicle in for each type of vehicle is an aircraft designed solely to the requirements of the NASA UAM reference passenger transport UAM mission, and generally without consideration for other missions. Excursions are performed by taking one of these vehicles and designing it for the additional requirements of a public good mission or missions. A variant is an aircraft which is configured for a specific mission at time of construction, for example the UH-60M versus the MH-60S. An aircraft might be reconfigurable in the field to perform different missions, with mission equipment and furnishings changed for different missions.

In the present study, an excursion is performed to meet both commercial passenger transport and public good missions, with the aircraft configured as appropriate for each mission, and carrying “scar” features to allow performance of the missions as either a variant or field configuration.

For an initial study, we consider examples of the NASA tiltwing aircraft as representative of VTOL vehicles which have good cruise endurance and a higher cruise speed at the cost of hover efficiency. NASA quadrotor vehicles will represent vehicles with lower cruise endurance and lower cruise speed, but greater hover efficiency.

Equipage

In each mission, a peculiar set of equipage may need to be installed and operated aboard the aircraft. Items such as avionics, antennae, inceptors, sensors, fittings, furnishings, and lighting may be required to perform a mission, in addition to the aircrew and payload.

Equipage may be permanently installed, or configurable with varying degrees of difficulty and time required. For this design study, no effort has been made to estimate an optimal allocation of equipage, but this is an area of future research.

PUBLIC GOOD MISSION CATEGORIES

While many use cases exist for vehicles which may serve the public interest, public good missions may be characterized by providing a benefit to a larger segment of the population than the Urban Air Mobility air taxi user base, or by providing a standby capability which is made available in an emergency. There are philosophical definitions of public goods, which include attributes such as non-rivalry and non-excludability (Ref. 15). This definition encompasses activities which are performed for-profit, such as medical services, humanitarian aid, public utility maintenance, and agricultural survey.

Since many similar activities may be performed on either extraordinary or more routine bases, two categories of missions are considered. The two categories considered in this paper are Humanitarian Assistance/Disaster Relief and Daily Public Good. Any given mission, like search and rescue or infrastructure inspection, could be performed in either category, but these categories can help frame the mission trade space with regard to the expected cost sensitivity, reconfiguration time sensitivity, availability of other solutions, and infrastructure support available.

Humanitarian Assistance and Disaster Relief (HA/DR)

Disaster scenarios include tropical cyclone (e.g. hurricane), earthquake, fire, flood, tornado, tsunami, volcano, and winter storm events. Some characteristics of these disasters that motivate developing aviation solutions include widespread needs for life-saving and life-sustaining support, widespread damage to infrastructure, and an overwhelming of the emergency services within the immediate area. In addition to straining and impeding the regional emergency systems, major ports, railways, and airports are often unusable in the immediate aftermath of a disaster, hindering the ability to bring new assets and supplies to the disaster area. Additionally, any new support crews brought to the area will place additional support burdens on the already-taxed systems. Aviation support is able to bypass chokepoints and provide services without placing undue extra burdens on the infrastructure.

The rationale for using UAM vehicles in these missions, despite their relatively small payload and range capabilities as compared to existing rotorcraft, is that a large number of vehicles and many dispersed operating bases are expected to be available in an economically vibrant UAM market. It is likely impractical to install the equipment for disaster relief operations on all the vehicles, but it is possible to make the fleet of vehicles compatible with such equipment for small penalties in space, weight, power, and cost (SWaP-C). In support of this hypothesis that a large number of smaller-capacity aircraft might be a good overall solution, the analysis of cost and capacity tradeoffs in mixed-fleet HA/DR performed by Chirgwin and Katakura (Ref. 16) calculated that deployment of the largest-capacity vehicles was often not the most cost efficient nor productive solution at a system level.

Cost sensitivity is often reduced in a disaster aftermath, as the lack of other options becomes the most motivating factor. There is a tension however, between this cost insensitivity at the time of disaster response with cost aversion in advance of a disaster, when expensive equipment must be procured, maintained, and stored with little apparent return on investment.

Wire strike events are more likely in the missions in support of public good in the aftermath of a disaster or other emergency operation. During UAM operations, the vehicles will be performing nearly all operations over the same established routes, allowing a complete survey of hazards. During an emergency, survey information may be incomplete, or no longer accurately represent the state of obstacles.

Daily Public Good (DPG)

Daily public good missions are those missions performed more routinely, and with a well-understood and often robust infrastructure backing the operations. The air traffic environment is likely to be well-ordered, and an emergency response operation is one of a small number of exceptions which need to be integrated into the airspace. Takeoff and landing sites are typically stocked and operating in anticipation of the air vehicles and their payload.

Some potentially hazardous events such as wire strike, rotor strike, and bird strike may be of less likelihood in normal UAM operations, but due to the ad hoc routing and changes to the operating environment, these hazardous events may need to be considered in the vehicle design and operation. A VTOL ambulance mission is a good example of a mission where operators today land and takeoff from ad hoc sites, and need to be more wary of interacting with the environment in an undesirable way, whether that be by rotor striking objects, or rotorwash eroding the ground and entraining ground debris.

MISSION DESCRIPTIONS

For each of the public good missions discussed in this paper, there are at least 12 basic attributes to consider for mission equipment and payload:

- Space
- Weight
- Power
- Layout
- Drag
- Mounting
- Range
- Endurance
- Speed
- Handling qualities
- Crew coordination
- Interaction with the environment

Space, weight, and power are classic parameters in aircraft design. Additionally, for each mission, there may some considerations of crew functions which need to be performed, handling qualities, and interaction with the environment.

The layout consideration is more than just a space claim; there are issues regarding accessibility, fields of view, and placement relative to other items for equipment and crew function. For instance, a hoist needs to be located with a free path below and beside it, and it needs to be located near an opening in the cabin where an operator can manipulate a litter or an evacuee. Additionally, the center-of-mass of the vehicle might be adversely impacted in some or all loading states by the changes to mass and mass distributions. Aircraft which change modes (convertiplanes), like the NASA UAM tiltrotors and tiltwings, require more careful consideration, due to their changing controls, higher operating speeds, and physical reconfiguration.

The drag of externally mounted devices may or may not be significant, and their placement for functionality may cause interference drag to increase. Many mission equipment items or configuration changes such as removing doors, can cause significant changes to the basic UAM vehicle drag. In extreme cases, these changes can impart loads which cause degraded handling qualities in various phases of flight.

Mounting and integrating non-standard equipment is not trivial, and if not planned at design time, may be impractical. Mounting holes, structural supports, electrical wiring, and pass-throughs are difficult to retrofit and certify later. By planning for public good mission uses, it is possible that a moderate engineering effort can provide items with little operational penalties in UAM passenger service, but greatly increase the utility for public good missions.

Mission range, endurance, and speed are similarly well-understood aspects of aircraft design, and these requirements may drive vehicle size growth or even preclude the feasibility of using a vehicle type in the mission.

The ability of an aircraft to perform precision maneuvers and station keeping in forward flight or hover, are key attributes which may lead to design requirements and constraints beyond those expected for a UAM passenger service vehicle. Hovering precisely to lower a hoist line to a victim can be a difficult operation, and can be exacerbated by local winds and recirculating flow. Flight control design and careful design of effectors can be effective remedies to deficiencies inherent to an aircraft.

Crew members on public good missions may need to perform a variety of tasks for mission success, such as performing a precise medical triage operation, manipulating a large and unresponsive victim, acting as an observer, or communicating with others in the response team and victims. These functions can be made more effective in a vehicle with lower cabin noise, with larger cabins, with less vibration, with better environmental conditioning, among other features. Rather than quantifying those attributes here, the present study acknowledges them and highlights some potential challenges. Design remedies exist for many of these issues, with varying applicability to each aircraft.

To fly, these vehicles move large quantities of air, and in hover, a strong downwash and outwash may be generated. The vehicle's downwash can directly erode the ground, push victims down, and become a potentially destabilizing recirculating flow. Outwash can also push victims away, destabilize people as they stand or walk, cause further damage to structures, create injurious projectiles, and cause loss of visibility or disorientation. In general, lower disk loading is the most powerful remedy, but some interactions can also be addressed by moving rotor placement.

Eight public good missions are identified, with a short summary provided for most of the missions. The missions are listed alphabetically in Table 6, and described below in the same alphabetical order. Two missions, the HA/DR missions of Communications Node and Search and Rescue at Sea, are described in detail in this paper; results are presented for two aircraft types, the quadrotor and tiltwing, which represent the two extremes of disk loading among the NASA UAM reference aircraft.

Communications Node (Comms Node)

Rationale: In HA/DR environments, the communication infrastructure is often disrupted, meaning that wired and wireless phone service may be unavailable. The communications node mission uses a vehicle to essentially place a powered cell phone tower in the air, to allow communication within its "cell" and connecting this cell to outside networks. This is not a persistent need, which would be more suited to a High-Altitude Platform Station (HAPS) vehicle or satellite service. The envisioned use of UAM could be similarly called a Low-Altitude Platform System (LAPS). A communications node is needed in the immediate aftermath of the disaster and is redundant and cost-inefficient after terrestrial services are restored. Thus, the ability to rapidly deploy the hardware, either on a dedicated airframe, or as a field modification to a commercial UAM vehicle, is necessary for this LAPS to make sense.

The Federal Communications Commission (FCC) published a white paper in 2011 (Ref. 17), which highlighted the need for restoring communication services following a disaster, particularly within the first 72 hours. The FCC's envisioned deployable aerial communications architecture (DACA) would be active within 12-18 hours and temporarily restore communications, including broadband, for 72-96 hours. In the suite of potential platforms considered in the DACA white paper, a small "suitcase" system was suggested for operation in low-flying aircraft such as general aviation fixed wing and helicopters. Similar proposals for low-altitude broadband systems in the aftermath of a disaster have been made by residents of other nations, for example in Indonesia (Ref. 18), where authors surveyed the impacts of earthquake, tsunami, flood, and volcano events on a widely-distributed population spread across many islands, and articulated the value of these LAPS-type systems.

For the proposed Comms Node mission, we will assume that a commercial UAM vehicle will be configured in the field to accept a communication relay mission equipment package, which has been previously designed, procured, and positioned near enough to the disaster area to be available in the immediate aftermath, in line with the FCC DACA vision. Therefore, the vehicle needs to have certain connections and mount points preinstalled for rapid configuring at the time of need.

The use of cell phone voice and broadband communications, rather than providing service for a dedicated emergency response communication protocol, restores communications to a large potential audience, allowing them to self-report status and raise issues as they observe them with hardware they already possess and know how to use. Because this mission requires a precise flight profile flown over a relatively long period of time, the aircraft will carry hardware producing a higher level of electromagnetic radiation, and the mission equipment would interfere with the use of the vehicle in passenger carrying roles, an optionally crewed aircraft may be preferred to a crewed vehicle.

Mission equipment package: The mission equipment package for Comms Node is summarized in Table 7. The main mission equipment components of the communications node are antennae, power supply, and shielding for the on-board occupants. As an example of a possible mission equipment package, we can use the example of equipment typically located on a terrestrial cell phone tower. The components of a cell tower's package include antennae, transceivers, power management, thermal management, and supporting structure.

For fuel or battery in the cabin or other auxiliary tanks, some kind of connections to the vehicle's propulsion energy system is required. Connection to the mission equipment power system is also required. For each of these systems, some kind of power conditioning is necessary, including changing voltage and changing between direct and alternating currents.

Space: Little internal space is required for the radio frequency elements, but power conditioning and extra fuel may occupy a significant portion of the cabin.

Weight: The weight of terrestrial cellular equipment is not optimized for aviation use, but by using this equipment, a significant cost savings can be realized, potentially making it feasible to procure, maintain, and store such equipment in or near to the disaster area.

Power: The power for cellular communications is small compared to the power required for a VTOL aircraft, and the biggest concerns are providing a power connection and regulating the voltage supplied to the cellular equipment.

Layout: An unobstructed 360-degree, lower hemisphere field of view for the antennae is desirable, but unobstructed 180-degree field of view is probably the minimum requirement to ensure coverage within a circular orbit of the aircraft. The cabin is not the best place to put the antennae, since only the side doors are available in the UAM aircraft, limiting field of view forward and aft. A package which protrudes from the side doors may be feasible, but certain vehicles like the tiltwing may have mechanical interference in helicopter mode. If off-the-shelf antennae are repurposed for the Comms Node mission equipment, then it is necessary to consider that radiation pattern of terrestrial cell phone tower antennae have 120-degree coverage sectors, so three antennae cover 360 degrees laterally. The vertical radiation pattern is much tighter, about 20 degrees included angle. For terrestrial applications, multiple sector sets are then required to cover vertical segments of the hemisphere. The placement and size of the antennae lead to some significant additional design requirements compared to the UAM passenger mission: power must be routed to a port where the mission equipment is mounted on the exterior of the vehicle, external mounting points are needed, the landing gear length for passenger loading may limit the available space for antennae, and aerodynamic forces on the external features will reduce efficiency and change vehicle trim moments. Specialized equipment controls are also required, to stow/deploy, activate/inhibit functioning of the mission equipment and monitor the communication performance. Typical terrestrial antennae are about 3 feet high (0.9m).

In the UAM passenger mission, the space underneath the passengers is designed to manage the occupant's acceleration profile as vertical velocity is taken to zero in crash, and non-deforming structure is counter to that goal. However, placement of mission equipment under the passenger portion of the cabin may be acceptable in the communications node application, because the passenger portion of the cabin is unoccupied. Because the passenger space is unoccupied, it also makes sense to install a fuel tank or battery in the cabin to provide mission equipment power and extend endurance.

Radius: Radius for the Comms Node mission is half the distance across a metropolitan area. For the present study, we consider the Los Angeles metropolitan area, with a required radius of approximately 20 nm. The distance is flown at best range cruise speed. In the event of a more widespread disaster, mission radii of closer to 100 nm might be necessary, with impacts to time on station and ferry time as aircraft are switched out.

Endurance: Endurance for a Comms Node mission should be long enough to minimize interruptions as aircraft are cycled off station, and to minimize the number of aircraft needed to provide uninterrupted service. For fuel-powered aircraft, long endurance comes with a manageable fuel load. The minimum time on station is probably on the order of 2 hours, with 4 or more hours being preferable.

Speed: There is a tradeoff of flight speed and orbit radius, which impacts LAPS vehicles more than HAPS vehicles, since the orbit diameter and the transmit range are much closer to the same value for LAPS vehicles. For a standard rate turn of 2 minutes per orbit, the bank angle and turn radius with airspeed are shown in Figure 10. The bank angle will impact performance via the load factor, but the bigger impact on mission performance will be due to the angles at which the antennae need to be pointed. A typical cell tower spacing is anywhere from 0.5 miles in a congested urban area to perhaps 20 miles in open areas. For the speeds of these vehicles, turn radius is not a major factor, and any of the vehicle flight speeds will work for a Comms Node, even in areas with a lot of building clutter. A flight speed of 100 kt is fast for these vehicles with the drag of a Comms Node, and 100 kt results in a bank angle of 15 degrees and a turn radius of 0.5 nm.

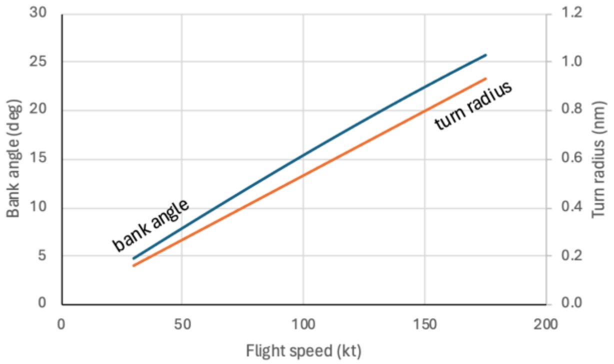

Figure 10. Turn radius and bank angle for standard rate turn orbits

Handling qualities: The large and variable drag on the underside of a vehicle performing the comms Node mission may make flying precisely difficult. A significant amount of flight testing is likely necessary to evaluate and remedy aerodynamic interference.

Crew coordination: The best way to use a vehicle like this is without a pilot onboard, and if one is necessary, then no crew coordination is probably necessary, as there is no need for multiple operators.

Interaction with the environment: We do not foresee particular difficulties interacting with the environment for this vehicle. Takeoff and landing will be from a prepared site, and enroute flight should be away from obstacles and other air traffic.

Quadrotor Results for Comms Node

Table 2 shows the sizing results when the turboshaft and battery powered quadrotors are sized for both a UAM mission and a Comms Node mission, with design gross weight and maximum takeoff weight selected to be the higher of the mission weights. DGW in the table is design gross weight, the higher of the mission takeoff weights among the design missions. WE is weight empty, which includes the permanently-installed batteries for hybrid and battery powered aircraft. WMTO is maximum takeoff weight, which is sized either as the design gross weight or as a takeoff capability at full power hover out of ground effect and sea level standard day. Mission GW is the weight at takeoff on the public good design mission. Cruise speed is the speed during the outbound level forward flight segment. Loiter speed is the speed during the orbiting potion of the mission serving as a Comms Node. Loiter time is the duration of the Comms Node segment.

The turboshaft powered aircraft has almost no weight growth, whereas the battery electric aircraft has significant growth. The weight growth for the battery aircraft is significant, and to mitigate this, the mission loiter time has been reduced. If loiter time is 60 minutes as shown in the middle sets of columns, weight growth from the baseline battery aircraft is similar to the small growth seen in the turboshaft aircraft. Installed power grows quite a bit more for battery aircraft, with the aircraft sized for a 60 minute loiter Comms Node mission increasing installed power by 15% relative to the baseline UAM-only battery powered aircraft. In the far-right of the table, a 120 minute loiter excursion is shown. The empty weight of the vehicle grows by 18%. The onboard energy for the Comms Node mission is 98% higher than in the UAM mission for the 120 minute loiter Comms Node aircraft, meaning that a second full-capacity battery system needs to be installed in the cabin to perform the 120 minute time-on-station flight.

Cruise speed is on the order of 90 knots with the antennae stowed, and the loiter speed is 41 knots for the turboshaft or 49 knots for the battery aircraft, meaning that a 5 nm or larger turn diameter is possible, with about 7 degrees of bank angle. The weight of the mission equipment and auxiliary battery lead to a 53% growth in installed power, which also justifies the reduced time-on-station, as any greater growth would probably add significant cost to the UAM aircraft fleet.

Table 2. UAM quadrotor vehicle designed with Communications Node as additional design mission

	Turboshaft		Battery – Vary loiter time			
	value	Δ%[a]	value	Δ%[a]	value	Δ%[a]
DGW (lb)	2990	+1%	5147	+3%	6483	+29%
WE (lb)	1832	+2%	4137	+3%	4713	+18%
WMTO (lb)	3268	+1%	5367	+7%	7043	+40%
Inst. pwr. (hp)	464	+1%	606	+15%	802	+53%
Mission GW (lb)	2721		4437		6483	
Cruise speed (kt)	92		80		86	
Loiter speed (kt)	41		46		49	
Loiter time (min)	240		60[b]		120[b]	

[a] Percent growth relative vehicle sized for UAM mission only
[b] Loiter time reduced to limit weight growth of battery vehicle

Tiltwing Results for Comms Node

The tiltwing results are summarized in Table 3. As with the turboshaft quadrotor, little growth is seen in the fueled turboelectric aircraft. The growth of the electric aircraft was more sensitive, with a reduction of loiter time to 60 minutes required to keep weight from rapidly growing. Increasing loiter time much more than 60 minutes caused the aircraft to grow without bound during sizing, and a closed design was not possible with 120 minute loiter.

Table 3. UAM tiltwing vehicle designed with Communications Node as additional design mission

	Tiltwing-turboelectric		Tiltwing-battery	
	value	Δ%[a]	value	Δ% [a]
DGW (lb)	5662	+4%	8292	+6%
WE (lb)	4320	+3%	7272	+7%
WMTO (lb)	5662	+4%	8292	+6%
Inst. pwr. (hp)	1146[b]	0%	2480	+9%
Mission GW (lb)	5661		8292	
Cruise speed (kt)	119		101	
Loiter speed (kt)	90		100	
Loiter time (min)	240		60[c]	

[a] Percent growth relative vehicle sized for UAM mission only
[b] Turboshaft power; generator and sum of motors similar
[c] Loiter time reduced to limit weight growth of battery vehicle

The loiter speed of the tiltwing is higher, between 90 and 100 knots, which results in a bank angle of about 15 degrees and an orbit of 10 nm diameter. The image in Figure 11 depicts the aircraft while orbiting. As can be seen, the antennae may need to be positioned differently to ensure good coverage on the ground, and much more bank would cause the wing to block some of the field of view.

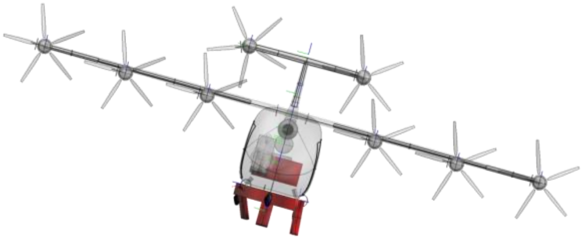

Figure 11. Front view of tiltwing with deployed Comms Node antennae flying an orbit at 100 kt and 15 degrees bank

Crew Transport

The crew transport mission is envisioned as a HA/DR mission for repositioning of personnel. Differences from a UAM passenger transport mission are the unprepared or semi-prepared operating sites on either end of a transport leg, and the necessity to provide storage for bulky and heavy equipment which the crews may need to carry with them.

Fire Suppressant

The fire suppressant mission is a HA/DR scenario where the vehicle would be used similar to current helicopters, with a slung load bucket which can be used to fill and empty fire suppressant. A number of additional sensors could be added to improve capability, but a basic capability to connect a bucket and actuate its opening and closing could provide a timely resource in the early stages of a fire. Handling qualities for this mission may be a challenge, with reduced visibility due to smoke and darkness, strong winds over uneven terrain, fire-induced winds, and high pilot workload near unfamiliar terrain. Striking the terrain is a major risk in this mission. Advanced vehicle technologies are currently being explored by NASA and others to address some of these challenges (Ref. 19).

Search and Rescue at Sea (SAR-at-sea)

Rationale: Search and rescue at sea, as a disaster relief use case, is a mission performed by rotorcraft today. The UAM vehicle version of this mission will be performed relatively near a shore. One such example is searching for and rescuing people in the water who have been swept out to sea by a tsunami, for instance the 2011 Tohoku earthquake and tsunami in Japan, which swept a person approximately 10 miles out to sea before he was rescued two days after the initial event (Ref. 20). Another disaster which might create the need for this mission is as a result of people seeking shelter from some onshore danger, like the 2023 wildfires on Maui Island, USA, where tens of people sought shelter from flames in the water of the harbor (Refs. 21 and 22). A third example is not literally at sea, but similar in many respects: when people become imperiled within a large land area inundated by flooding such that terrestrial transportation is impractical. Flooding of this type occurred in 2005 when Hurricane Katrina was followed a month later by Hurricane Rita, striking the Gulf Coast of the United States, imposing wind damage to structures and infrastructure, accompanied by widespread flooding, including approximately 50 square miles in the city of New Orleans flooded to a depth of 3 feet or greater (Ref. 23, see also Refs. 24 and 25). In these types of disaster events, transit distances from the operating base to the search area may be within a relatively short range for aviation, due to inherent dispersal of UAM vertiports and the limited scope expected for such a vehicle, freeing traditional rotorcraft to search at longer ranges.

Mission equipment package: Mission equipment includes the items in Table 8, with weights and power estimated from similar items in existing rotorcraft which perform SAR missions at sea (data references for the military aircraft are not publicly available). These mission items might be arranged around the vehicle as shown in Figure 12 and Figure 24, translucent renderings of the quadrotor with the SAR-at-Sea mission equipment items depicted in red. One item which is not counted in the sizing results shown here, but may be important if flooding is the scenario, is a wire strike kit. Helicopters performing emergency medical services often have wire strike kits installed to cut power line and other wires that the vehicle might inadvertently strike while flying into or through an un-surveyed or compromised area, and this is more likely over inundated land than at sea.

Space, weight, power: The space, weight, and power for search-and-rescue components have been estimated by examining the equipment lists for helicopters which perform similar missions for military and civilian agencies.

Drag: Drag has been estimated by using wetted areas, frontal area, shape factors, and including interference drag between the exposed mission equipment and the airframe.

Mounting: Mounting and connections for power and control are needed for the hoist, electro-optical/IR sensors, and internally stored components. The internally-accessible baggage compartment at the front-left of the cabin is used to store medical supplies.

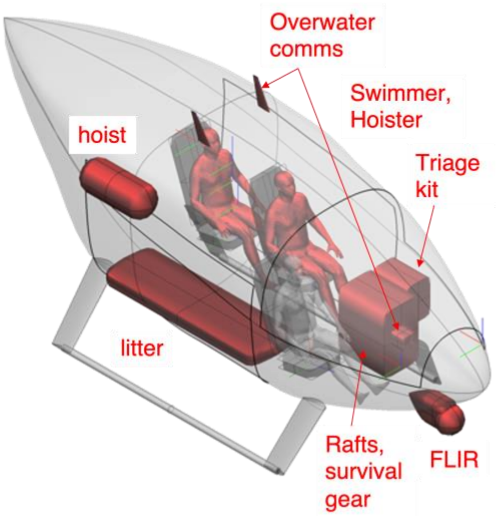

Figure 12. Illustration of quadrotor fuselage in SAR-at-Sea configuration with Mission Equipment and specialized crew shown in red.

Radius and endurance: To determine a specification mission radius and endurance for SAR-at-Sea, the authors biased toward longer time-on-station, acknowledging that finding a person in the water is a very difficult task in normal conditions, and the conditions during a disaster are more difficult, with debris in the water, smoke in the air, rougher seas, and grime on the victims all contributing to lower effectiveness of visual detection. Justification for the practicality of a shorter mission radius is primarily the ubiquity of potential operating bases in a mature UAM network.

A mission radius of 10 nm was selected as a round number that also covered the shoreline near 5 selected metropolitan areas while operating from existing airfields and heliports: Los Angeles and Orange Counties, California; San Francisco Bay Area, California; Tampa Bay, Florida; Hampton Roads, Virginia; and eastern Puget Sound, Washington. The coverage of the San Francisco Bay Area with only 5 existing operating locations is shown in Figure 13, and it can be observed that nearly all the urban and suburban shoreline is covered. The uncovered regions can be covered with less time on station, reducing search time by 1.7 minutes per nautical mile of additional radius for the turboshaft quadrotor. In Figure 14, two existing airfields and one existing heliport are added, with nearly redundant coverage in all but southeast San Pablo Bay in the upper-right of the map, which still is unserved by existing aerodromes withing 10 nm. The map images were generated using *gcmap.com*, and are 2-dimensional projections, hence they appear non-circular in the images (Ref. 26).

Figure 13. San Francisco Bay Area SAR-at-Sea coverage with vehicles operating up to 10 nm from 5 existing airfields and one heliport

Figure 14. Nearly complete and redundant coverage of the San Francisco Bay Area operating SAR-at-Sea from 7 existing airfields and 2 existing heliports

Speed: The speed of the vehicles is likely of less importance than in other applications, as the 10 nm range is short. What is lost in speed is made up for by proximity.

***Handling qualities*:** Good hover precision and maneuverability are desirable. Often, a flight mode where the hoist operator is given limited translational control authority for the aircraft is beneficial for lowering the hoist precisely.

In the aftermath of a disaster, or while one is still causing severe weather, steady and gusting winds will likely be higher than in normal weather, placing a greater demand on flight controls.

Crew coordination: A significant amount of coordination among the crew will improve outcomes. Searching for victims, placing the vehicle over a hoist location, and triage of the patient are all activities where the ability to communicate, see, and move around may be necessary. A spacious cabin and good communication equipment help ensure success.

Interaction with the environment: Operating over civilians and in unprepared areas make it necessary to have a vehicle that does not have strong downwash or outwash, can tolerate gusts and steady winds, and can fit into a small area without striking obstacles.

4-view drawings of some of the NASA UAM reference vehicles configured for SAR-at-sea are shown in Figure 22 through Figure 26. Of note are the similarities in placement which are possible, and the challenges which come from having a wing near the door. A low wing would make hoist operations in this mission difficult, if not impossible.

Quadrotor Results for SAR-at-sea

Quadrotor results for SAR-at-sea are shown in Table 4. The growth in the vehicle is a bit larger for turboshaft powered aircraft than seen in the Comms Node mission, but the battery-powered vehicle is less sensitive than in the Comms Node mission. The growth for the turboshaft vehicle appears to be manageable.

Table 4. UAM quadrotor vehicle designed with SAR-at-sea as additional design mission

	Quadrotor-turboshaft		Quadrotor-battery	
	value	Δ%[a]	value	Δ%[a]
DGW (lb)	3237	+9%	5643	+13%
WE (lb)	1900	+5%	4378	+9%
WMTO (lb)	3394	+5%	6221	+24%
Inst. pwr. (hp)	471	+2%	716	+37%
Mission GW (lb)	3122		5443	
Cruise speed (kt)	110		93	
Loiter speed (kt)	53		55	
Loiter time (min)	30		30	

[a] Percent growth relative vehicle sized for UAM mission only

A rendering of a hovering quadrotor vehicle hoisting a rescued person and crew member during a SAR-at-sea mission is shown in Figure 15. Note the sliding door and the mounting of the hoist above the door opening. In this example operation, the litter is not used to evacuate the victim. The low disk loading of the quadrotor and rotors spaced away from the cabin likely mean that downwash will be a minor impact on the operation. See Figure 24 for the 4-view drawing of the turboshaft quadrotor with SAR-at-sea mission equipment and note the placement of rotors relative to the door and hoist.

Figure 15. Quadrotor hoisting rescued person and crew in SAR-at-Sea mission

Tiltwing Results for SAR-at-sea

The results for the tiltwing are shown in Table 5. The turboelectric tiltwing has slightly less percentage growth than the turboshaft quadrotor, and the battery-powered aircraft is much less sensitive than the battery quadrotor.

Table 5. UAM tiltwing vehicle designed with SAR-at-sea as additional design mission

	Tiltwing-turboelectric		Tiltwing-battery	
	value	Δ%[a]	value	Δ%[a]
DGW (lb)	5718	+5%	8251	+6%
WE (lb)	4352	+3%	6987	+3%
WMTO (lb)	5718	+5%	8251	+6%
Inst. pwr. (hp)	1148	0%	2345	+3%
Mission GW (lb)	5657		8052	
Cruise speed (kt)	146		149	
Loiter speed (kt)	86		118	
Loiter time (min)	30		30	

[a] Percent growth relative vehicle sized for UAM mission only

The 4-view drawing of the tiltwing in Figure 26 illustrates the main issues with using a tiltwing for this mission. The wing interferes with door and hoist access when at 90 degrees for hover, and the inboard high-disk-loading rotors are near the door and hoist. The hoist for this vehicle had to be placed further forward than in the other reference vehicles to clear the wing when tilted in helicopter mode.

Search and Rescue Over Land (SAR-land)

The Search and Rescue Over Land mission is similar to the SAR-at-sea mission in that it requires a transit flight to a search area, followed by a loitering search, and if successful, a hovering hoist operation. The major difference is that this operation is a DPG mission, expected to be performed from a fixed base with fully functioning support infrastructure. The mission is also more likely to be performed in a purpose-configured aircraft, with highly specialized crew.

Supply Transport

The supply transport mission could be a simple conversion to cargo operations. These missions have proven valuable in

HA/DR responses using helicopters and tiltrotors, and the most important considerations are probably ensuring that seats are removable, shown in Table 6 as a reduction in furnishings weight of 4 seats at 23 lb each. A different solution could be to carry an external slung load instead of carrying supplies in the cabin, which requires some mounting of a hook and a control to release the load. The supply transport mission could be the second easiest way to use UAM aircraft for public good missions, and may require no changes from the existing plans of UAM designers.

The mission is flown from some initial VTOL facility perhaps to a separate supply storage location, then on to a delivery point near the victims for distribution. The supply storage location and delivery locations may be ad hoc and semi-prepared, and may not offer opportunities for refueling and recharging. Many flight operations will likely need to be performed, perhaps going to multiple locations. Enroute speed may significantly improve productivity.

VTOL Ambulance

The VTOL Ambulance mission is a DPG mission which is similar to helicopter emergency medical services (HEMS) operations currently performed by dedicated aircraft. The value of this mission is perhaps most easily understood among the public good missions listed here, since it has a direct analogy today, but more work is required by the authors to explore the best niche for UAM aircraft to supplement or replace HEMS and other services. If projections for low cost vehicles via large productions runs come to pass, then UAM VTOL Ambulance may make attractive low-cost solutions.

The VTOL Ambulance mission will likely involve a purpose-configured aircraft, with advanced medical equipment and supplies onboard, and require easy ingress and egress for a patient on a litter. The crew will often need to be able to move within the cabin during flight to tend to the patient. Flights would include landing at a remote unprepared location and taking the patient to a medical facility served by a dedicated heliport or vertiport.

VTOL Evacuation

VTOL evacuation is a HA/DR mission where VTOL assets are used to evacuate people stranded in unsafe places, where only a VTOL landing is possible. The operations would return to a central base in most cases, but could also make shorter flights between an unsafe location and a nearby safe location. A key attribute is that many such evacuation flights will be necessary, with many people stranded perhaps in a single or multiple locations. Some example locations are a high-rise building experiencing a fire in the middle floors or people cutoff from escape by wildfire or flooding.

The mission likely requires no change to an aircraft designed for UAM passenger transport, except perhaps increasing the onboard energy storage. In this mission, the only significant differences from normal operations are the degradation of infrastructure and the possibility of operating to unusual landing sites. While the VTOL Evacuation mission can be performed without modifying aircraft, the challenges of operating outside of normal procedures should not be taken lightly, and significant restrictions will be necessary unless additional equipment is installed. Another difference is that the mission may be flown with multiple flights between refueling or recharging, and partial recharge at the remote pickup location will not be available.

SUMMARY

In this study of the design implications of UAM vehicles performing public good missions, eight possible public good missions were presented, and two disaster-related missions have been described in more detail. For the Communications Node and Search and Rescue at Sea missions, the addition of public good mission considerations during the design stage was evaluated for high- and low-disk loading vehicles. Some of these additional design considerations could cause changes to vehicle layout, the addition of scar weight, and associated costs in development, production, and support.

The results show that even for missions which seem to have significant additional requirements for mission equipment and endurance it may be possible to design aircraft which can be reconfigured for these missions with modest incremental growth compared to a vehicle designed solely for a commercial UAM passenger transport mission. Fuel-powered vehicles are less sensitive to the growth from additional requirements, and advanced battery technology may permit battery electric vehicles to also be designed for reconfigurability with minor incremental growth.

Vehicle attributes, such as the placement of wings, rotors, doors, and hover disk loading, will make it more difficult to accommodate some public good missions. The baseline tiltwing, for instance, is not as well suited to hoist missions as the baseline quadrotor, although both aircraft require modifications to the layout and function of the doors if they are to be used for hoist operations.

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26. Maps generated by the Great Circle Mapper (www.gcmap.com) - copyright © Karl L. Swartz.

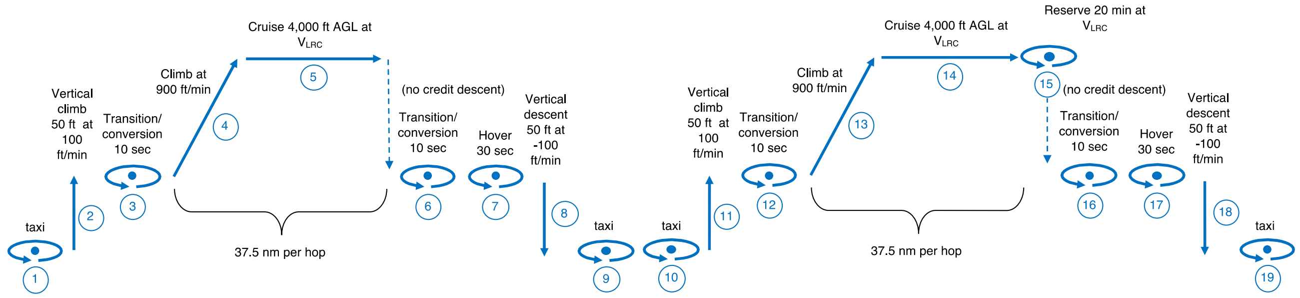

Figure 16. Mission stick figure for baseline UAM passenger mission

Table 6. Performance and equipment attributes of selected public good missions

Mission category	Mission descriptor[a]	Radius (nm)	Loiter (hr)	Space and layout considerations	Crew+Mission Equipment: Net weight[b] (lb$_f$ | kg$_f$)	Net power[b] (hp | kW)	Payload[b] (lb$_f$ | kg$_f$)
HA/DR	**Comms Node**	**30**	**2**	**Antennae, electronics, shielding, remove 4 seats**	**290 | 130**	**2.9 | 2.1**	**--**
HA/DR	Crew Transport	30	--	Seats, large doors, equipment storage	0	--	1200 | 540
HA/DR	Fire Suppressant	20	0.1	Pilot, communications, hook, sling, bucket, controls	320 | 145	1.0 | 0.7	1400 | 640
HA/DR	**SAR-at-sea**	**10**	**0.5**	**Communications, FLIR, hoist, exterior lighting, litter, triage supplies, water survival gear, large door, crew**	**1100 | 480**	**4.0 | 3.0**	**200 | 91**
DPG	SAR-land	20	0.5	Communications, FLIR, hoist, exterior lighting, litter, triage supplies, large door, crew	770 | 350	4.0 | 3.0	200 | 91
HA/DR	Supply Transport	30	--	Cargo floor, large door, remove 4 seats	(-92)	--	2000 | 910
DPG	VTOL Ambulance	30	--	Support equipment, medical supplies, litter, crew station	TBD	TBD	200 | 91
HA/DR	VTOL Evacuation[c]	10	--	Handicapped access	--	--	800 | 360

[a] Missions evaluated for this paper in **bold**
[b] Values rounded to 2 significant digits for table.
[c] Multiple flights per refuel/recharge

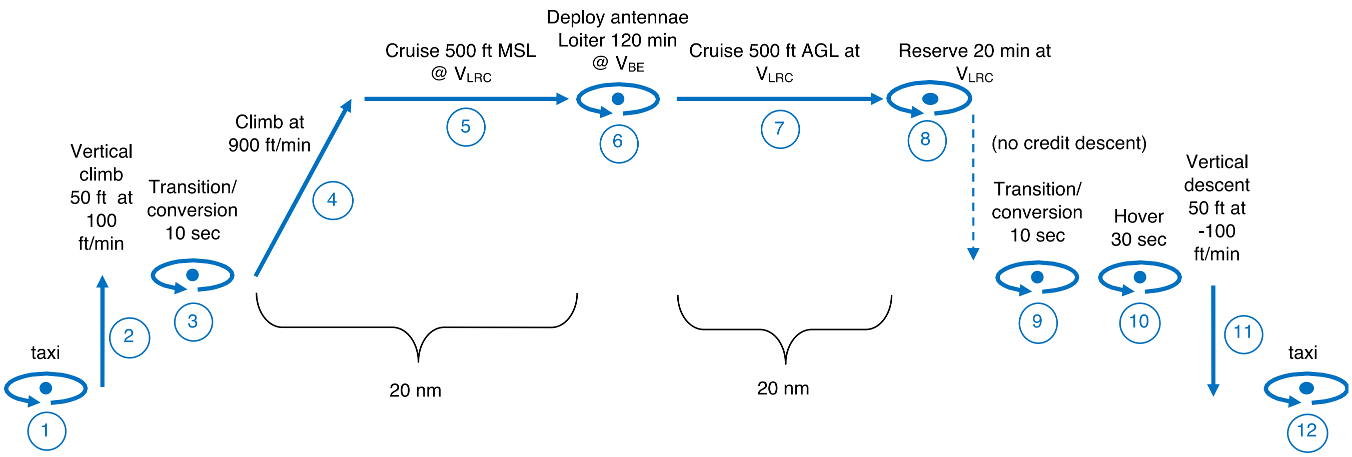

Figure 17. Mission stick figure for Communications Node

Table 7. Communication Node mission equipment

Mission Equipment Item (includes installation)	Space and layout considerations	Weight[a] (lb_f | kg_f)	Power[a] (hp | kW)	Drag[a] (ft^2 | m^2)
Actuators	Fit within fairing, stow and deploy antennae	12 | 5.4	0.17 | 0.13	--
Antennae (deployed)	3.0 ft tall x 1.0 ft wide, clear field of view	66 | 30	--	2.4 | 0.22
Electronics	Power, control data connections to vehicle	81 | 37	2.7 | 2.0	--
Fairings and mounts	Fit within landing gear space, stowed	104 | 47	--	7.2 | 0.67
1000 lb fuel tank (empty)	Use seat mounts, connection to fuel system	100 | 45	--	--
Remove 4 seats	Provide cabin space for fuel	(-92) | (-42)	--	--
Scar weight	Wires, connectors, mounting, fuel port	15 | 6.8	--	--

[a] Values rounded to 2 significant digits for table

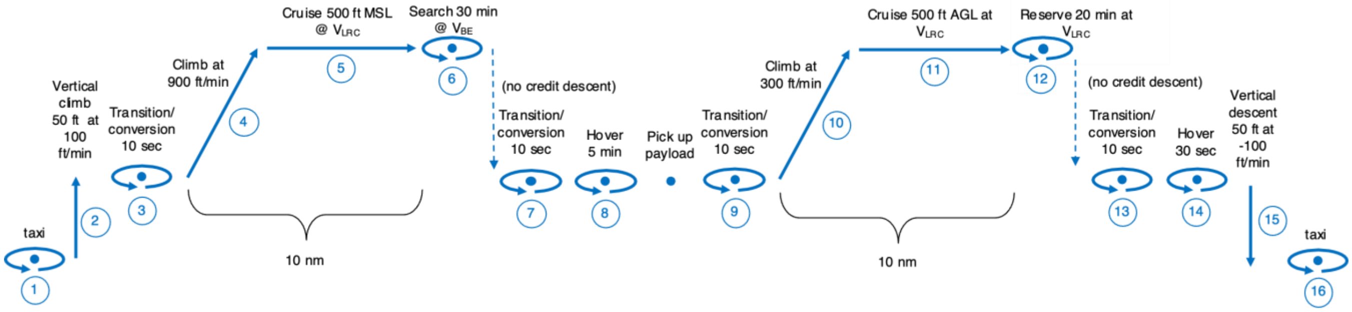

Figure 18. Mission stick figure for Search and Rescue-at-Sea

Table 8. Search-and-Rescue-at-Sea mission equipment

Mission Equipment Item (includes installation)	Space and layout considerations	Weight[a] (lb$_f$ | kg$_f$)	Power[a] (hp | kW)	Drag[a] (ft^2 | m^2)
Communications	VHF antennae	10 | 4.5	0.1 | 0.07	0.01 | 0.00
FLIR	0.5 ft dia. ball on turret	160 | 73	0.5 | 0.37	1.0 | 0.09
Hoist	Mounted above and next to door, clear path below and place for operator to see and assist	170 | 77	3.4 | 2.5	3.0 | 0.28
Litter	7 ft long by 2 ft wide	10 | 4.5	--	--
Triage supplies	Triage kits, blankets, water	30 | 14	--	--
Large door	7 ft wide by 4.5 ft high	--	--	--
Rafts and supplies	2 x 4-person rafts	60 | 27	--	--
Rescue crew	Pilot, hoist operator, swimmer	640 | 220	--	--
Remove: 2 seats	Open up floor space	(-46) | (-21)	--	--
Wire strike protection	Toward front of vehicle, protect rotors and landing gear entanglement	21 | 9.7	--	0.03 | 0.00
Scar weight	Wires, connectors, mounting	15 | 6.8	--	--

[a] Values rounded to 2 significant digits for table

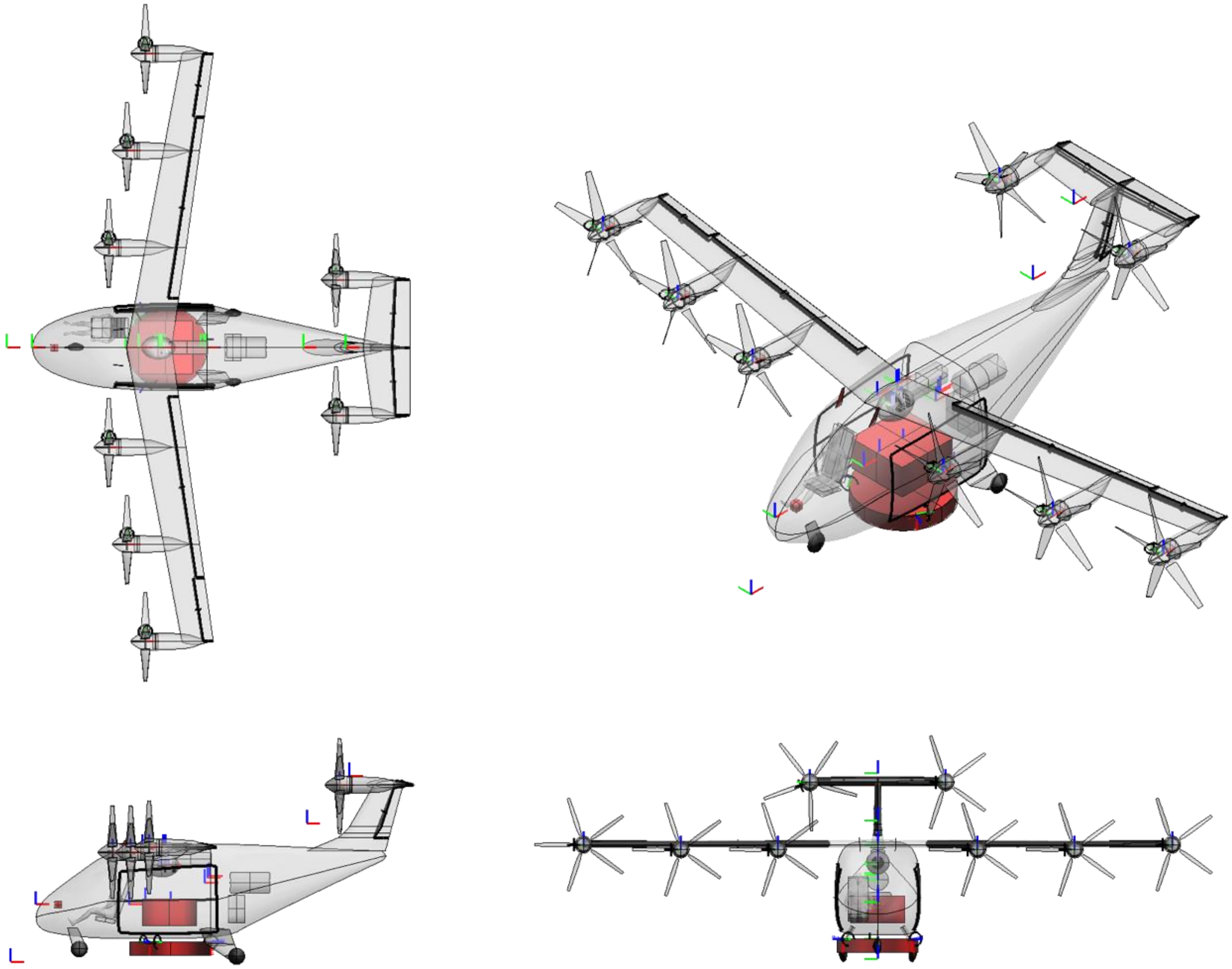

Figure 19. 4-view drawing of turboelectric tiltwing UAM vehicle in Communication Node configuration (stowed)

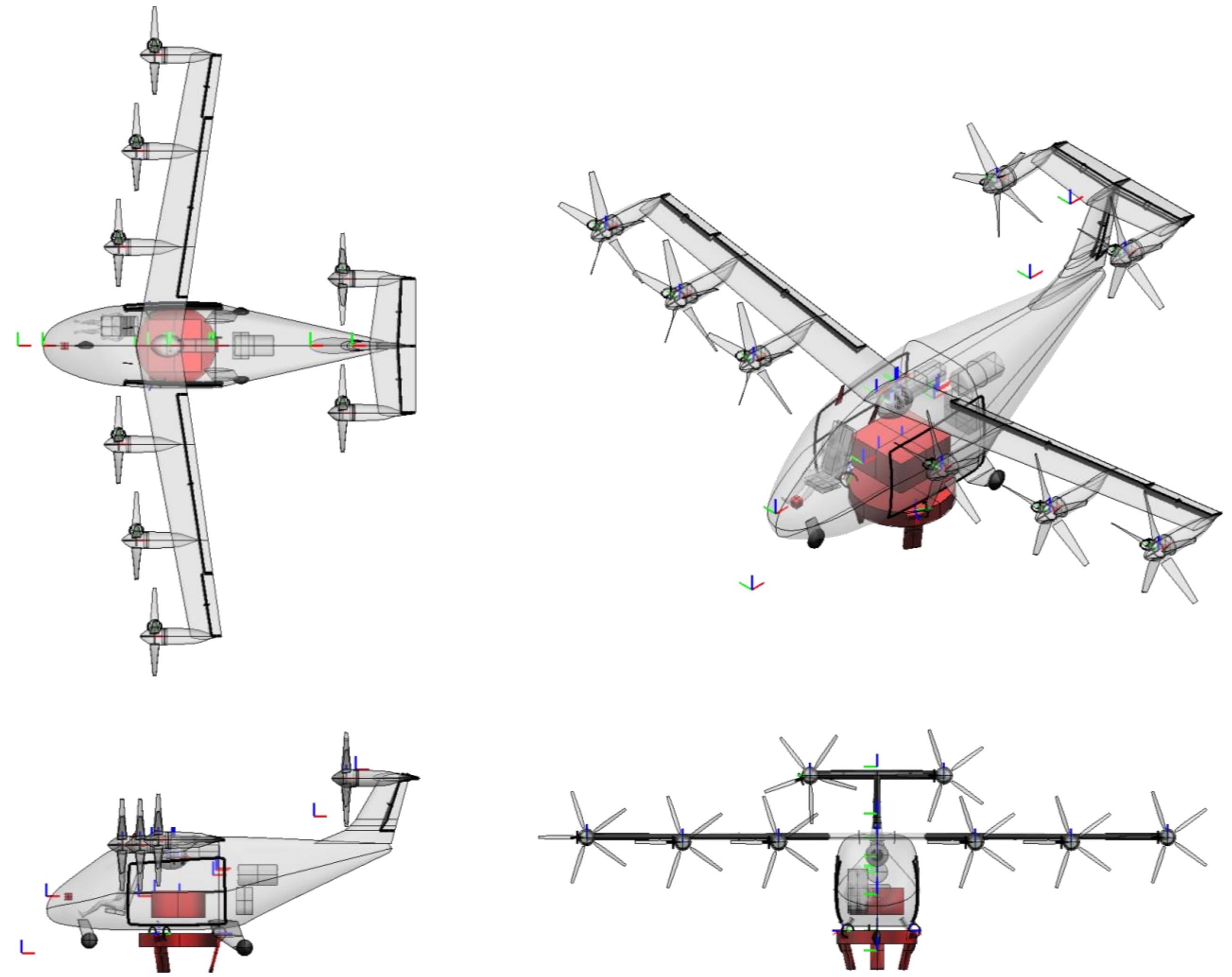

Figure 20. 4-view drawing of turboelectric tiltwing UAM vehicle in Communication Node configuration (deployed)

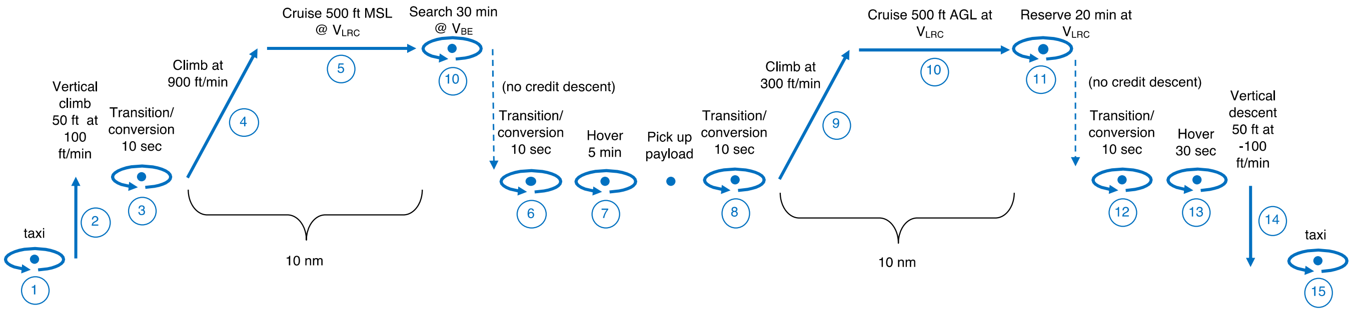

Figure 21. Mission stick figure of SAR-at-Sea mission

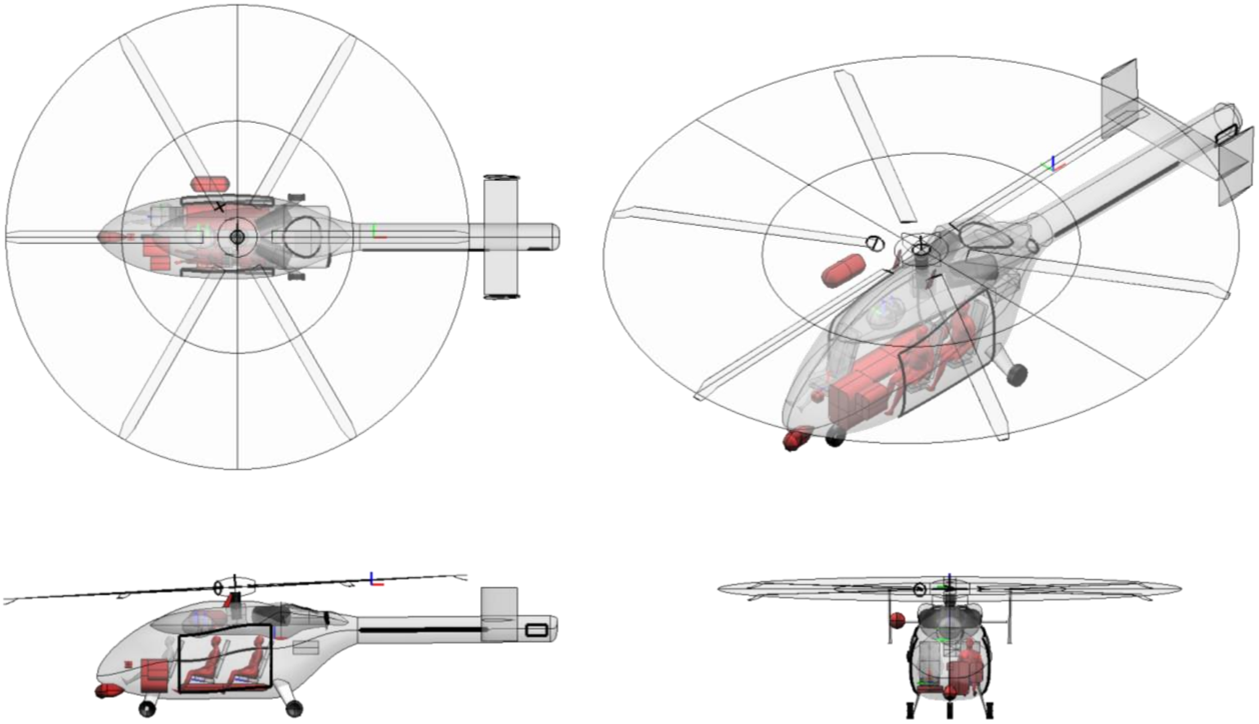

Figure 22. 4-view drawing of turboshaft QSMR UAM vehicle in SAR-at-Sea configuration

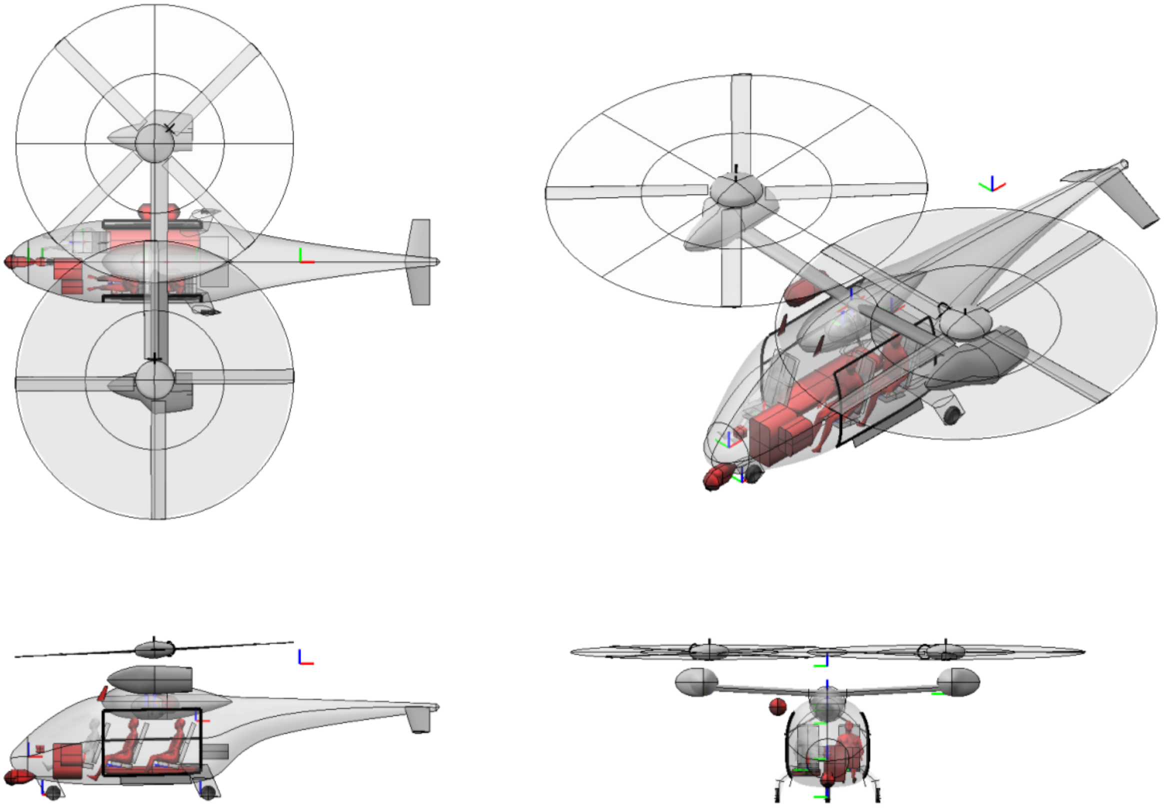

Figure 23. 4-view drawing of turboshaft side-by-side UAM vehicle in SAR-at-Sea configuration

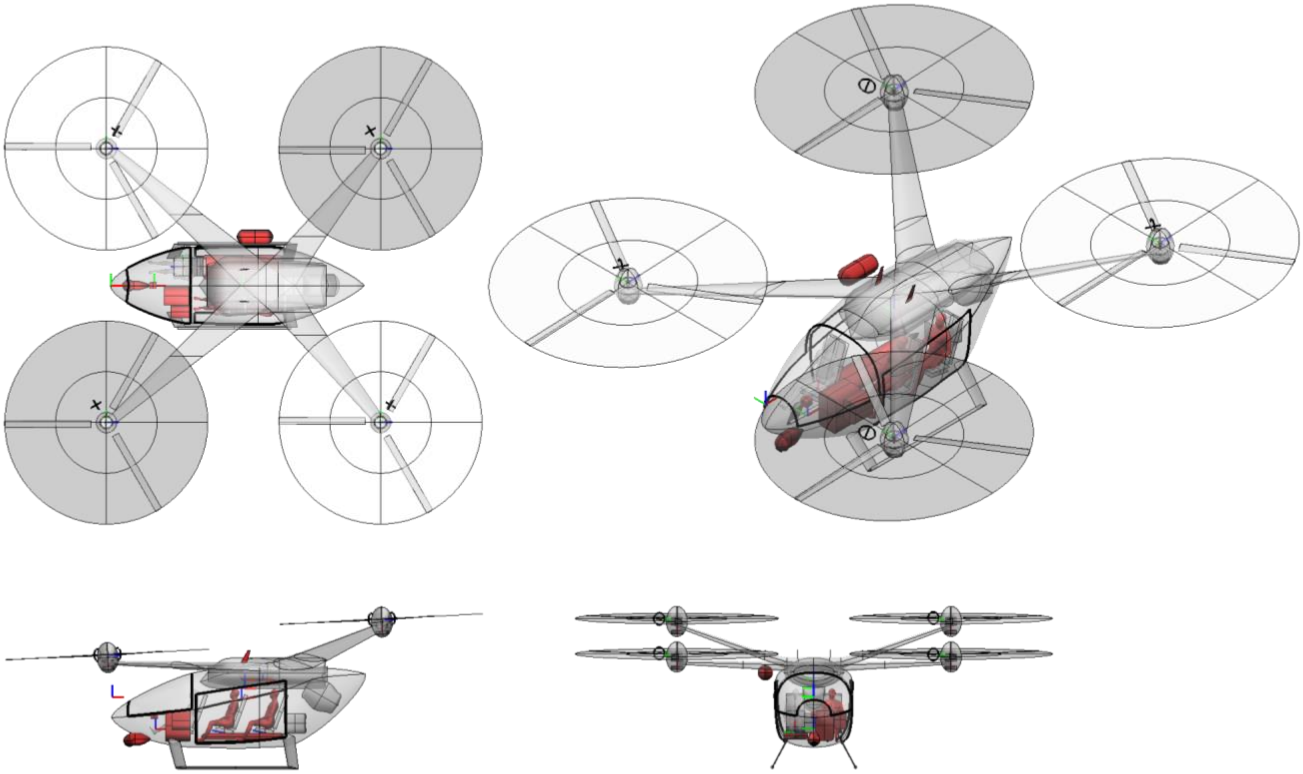

Figure 24. 4-view drawing of turboshaft quadrotor UAM vehicle in SAR-at-Sea configuration

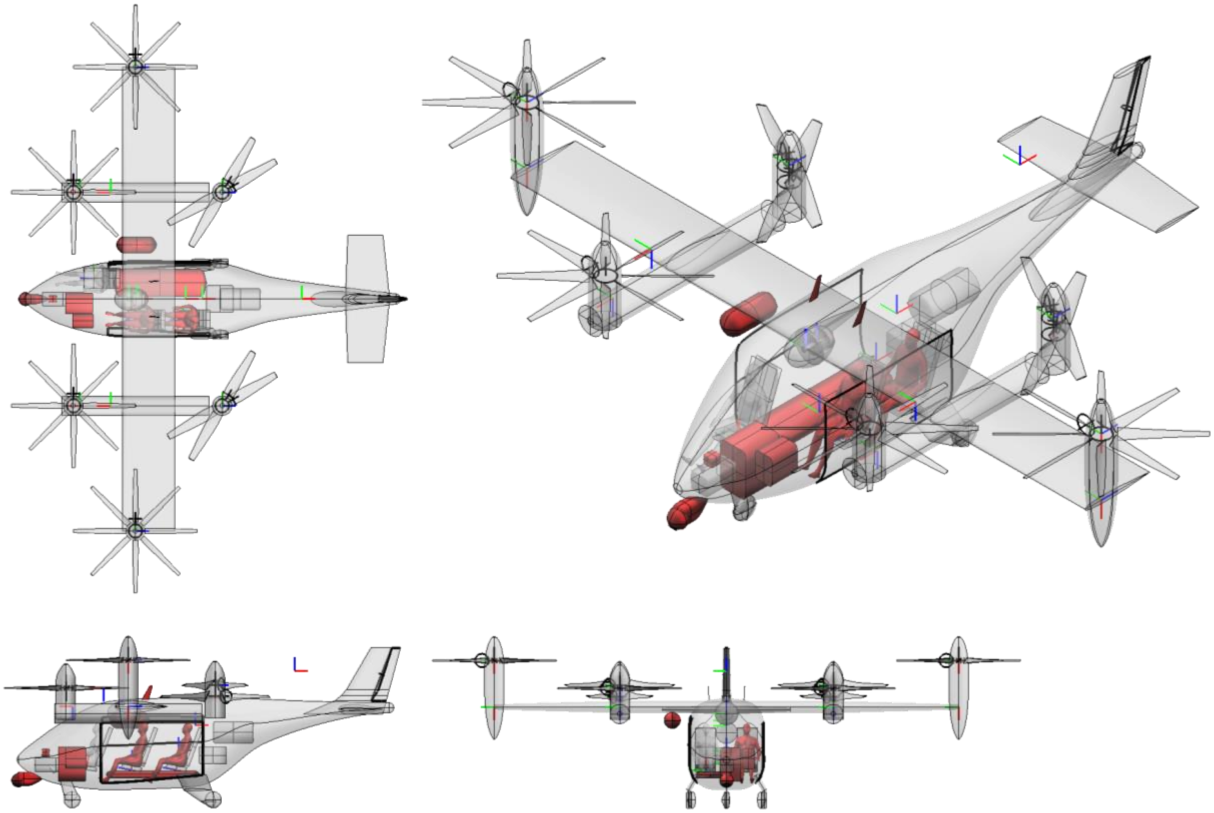

Figure 25. 4-view drawing of turboelectric multi-tiltrotor UAM vehicle in SAR-at-Sea configuration

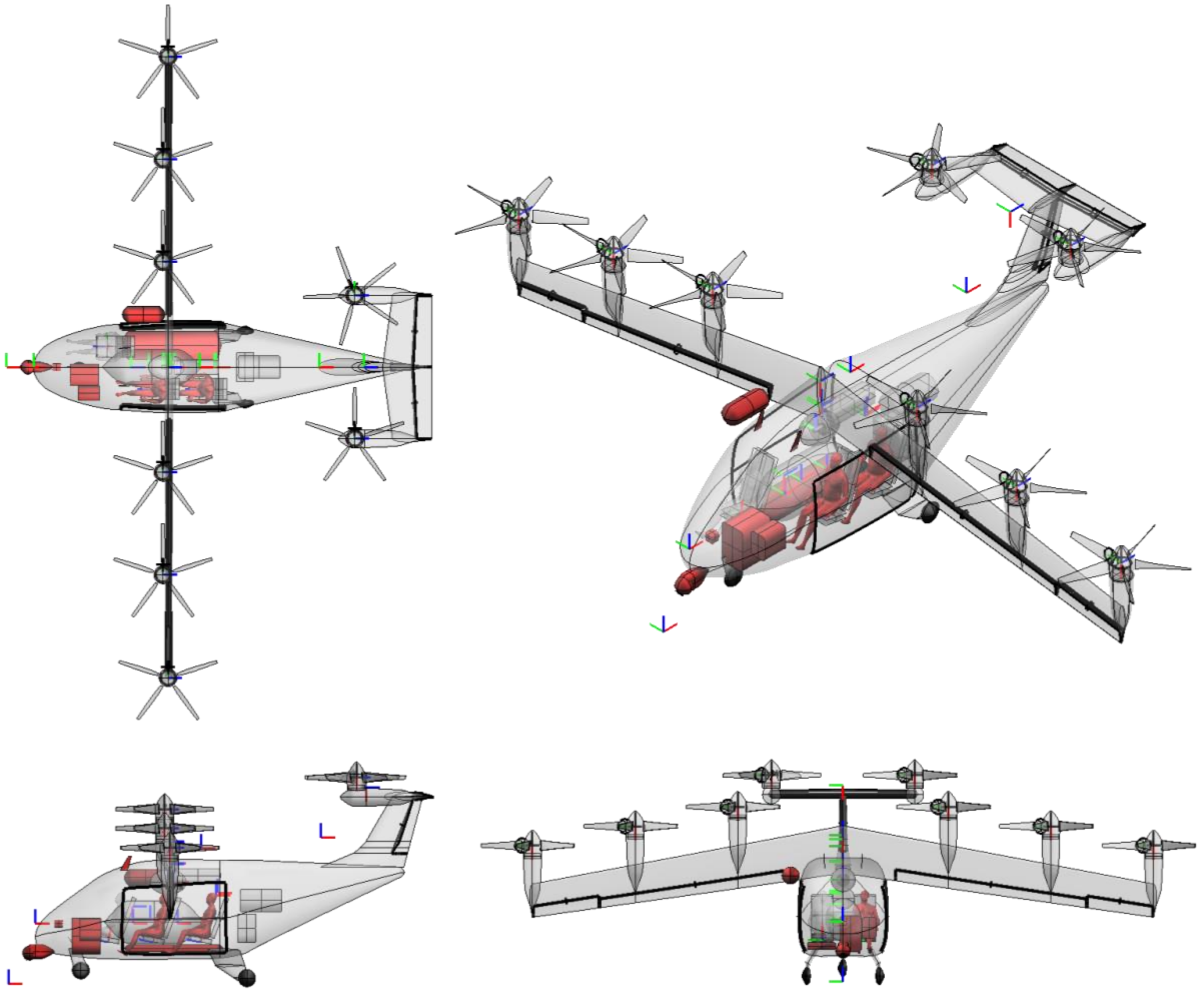

Figure 26. 4-view drawing of turboelectric tiltwing UAM vehicle in SAR-at-Sea configuration