Smart Precise Rotorcraft InTerconnected Emergency Services (SPRITES)

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The greatest utility for small autonomous vertical lift aerial vehicles may be for public service missions, particularly those related to disaster relief and emergency response (DRER). The current work focuses on novel vertical lift aerial vehicle designs that might be well suited for search and rescue (SAR) and small package aid delivery missions. In particular, a vehicle exhibiting efficient cruise, in addition to hover and vertical takeoff and landing capability, is a key attribute for a DRER vehicle. But, correspondingly, cost, simplicity, and community acceptance are also important considerations for such vehicles in conducting their overall mission concept of operations (CONOPS). Further, it is recognized that such DRER missions will need to be supported not just by one vehicle but, instead, by an intelligent network of vehicles to fully realize their full potentiality. Finally, it should be acknowledged that advancements in efficient-cruise small autonomous vertical lift aerial vehicles, ostensibly for DRER missions, will also have a significant cross-cutting technology application to other UAV missions.

Nomenclature

α = Vehicle angle of attack, Deg.
D_{A2} = Drag of aft tandem-wing at $\alpha = \alpha_2$
D_{F1} = Lift of forward tandem-wing at $\alpha = \alpha_1$
L_{A2} = Lift of aft tandem-wing at $\alpha = \alpha_2$
L_{F1} = Lift of forward tandem-wing at $\alpha = \alpha_1$
L_{S1}, L_{S2} = Lift of single, isolated wing at $\alpha = \alpha_1$ or $\alpha = \alpha_2$
GW = Vehicle gross weight (total mass), kg
P = Vehicle total lift/propulsion power, W
L/D_e = Vehicle effective lift-to-drag ratio; D_e=P/V
V = Vehicle cruise velocity, m/s
$\aleph$ = Tandem-wing lift interference parameter, $\aleph \equiv (L_{F1} + L_{A2})/(L_{S1} + L_{S2}) - 1$
φ = Tandem-wing lift-to-drag-ratio interference parameter,
$\varphi \equiv [(D_{S1} + D_{S2})(L_{F1} + L_{A2})]/[(L_{S1} + L_{S2})(D_{F1} + D_{A2})] - 1$

I. Introduction

REFERENCE 1 outlined some early perspectives of NASA Ames Research Center as to, among other things, the utility of autonomous vertical lift aerial vehicles for public service missions. This early work was followed up by Refs. 9-11, which focused respectively, to varying degrees, on public service missions, especially those related to disaster relief and emergency response (DRER) missions. From the time of this early work, a tremendous growth in small uninhabited aerial vehicle (UAV) research and development has occurred. In particular, small hobbyist or consumer-oriented multirotor "drones" have seen widespread adoption. In parallel with this overall growth in UAV's has been a substantial expansion of small vertical lift aerial vehicle research, some of which is summarized, in part, in Refs. 2-8 and 13.

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This paper will focus on the specific conceptual design and development issues related to a notional network of autonomous aerial vehicles for DRER-type missions. For informal descriptive purposes, vehicles responding to such notional disaster relief and emergency response missions are referred to herein this paper as SPRITES (Smart Precise Rotorcraft InTerconnected Emergency Services); Fig. 1a-b. This current work immediately builds off of concepts and ideas presented in Ref. 13.

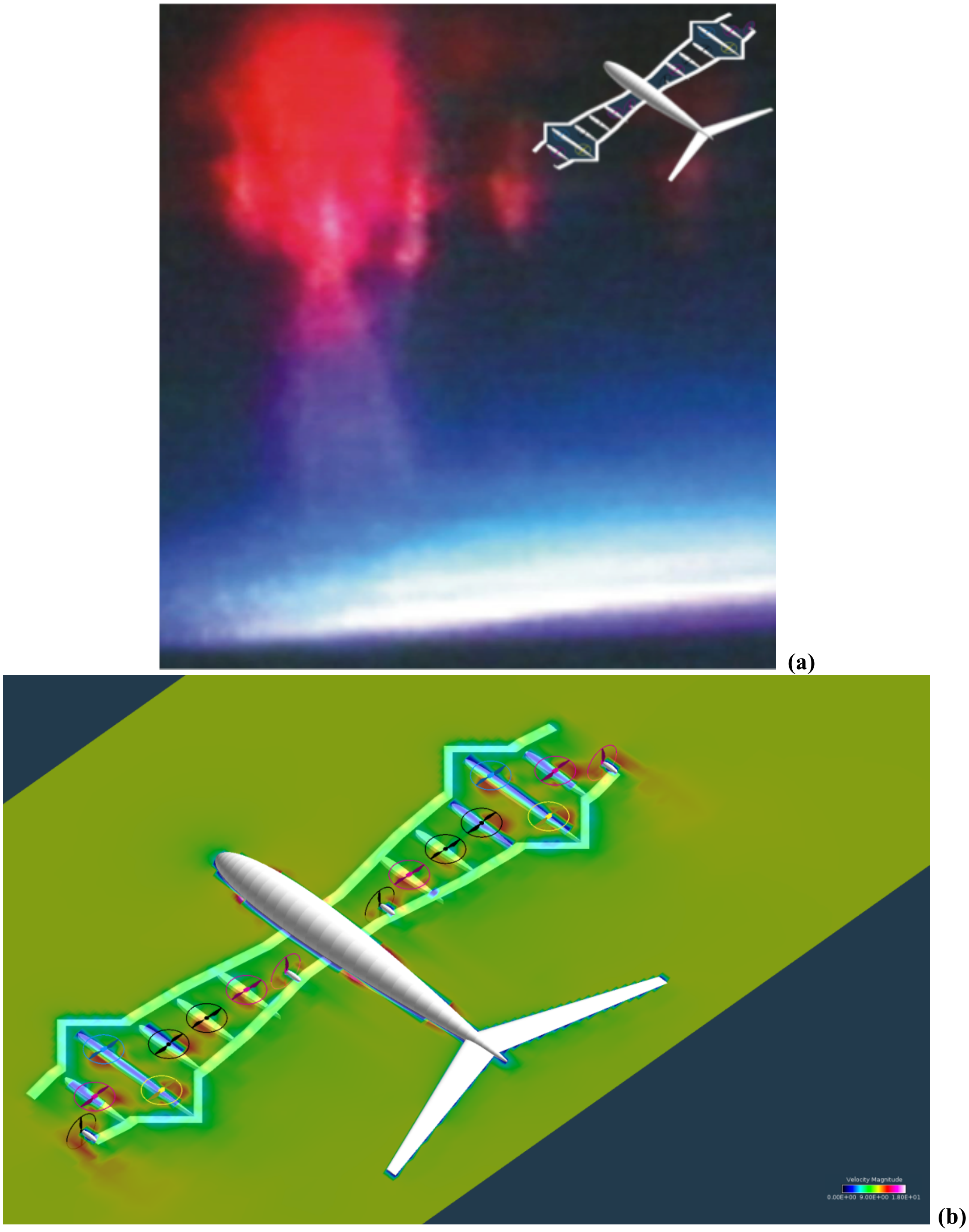


Figure 1 – SPRITES: (a) notional heterogeneous multi-rotor configuration and its partial-namesake upper-atmosphere electrical phenomena and (b) computational result for the vehicle configuration

The Fig. 1 notional vehicle is an attempt to merge the simplicity of multirotor (a heterogeneous mix of lifting-rotors and propellers) configurations with fixed-wing lifting-surfaces to arrive at an efficient-cruise "compound" rotorcraft. .[†]

Figure 2 illustrates a very high level description of emergency response missions/use cases that are representative of the applications to be studied as a part of future NASA rotorcraft research efforts.

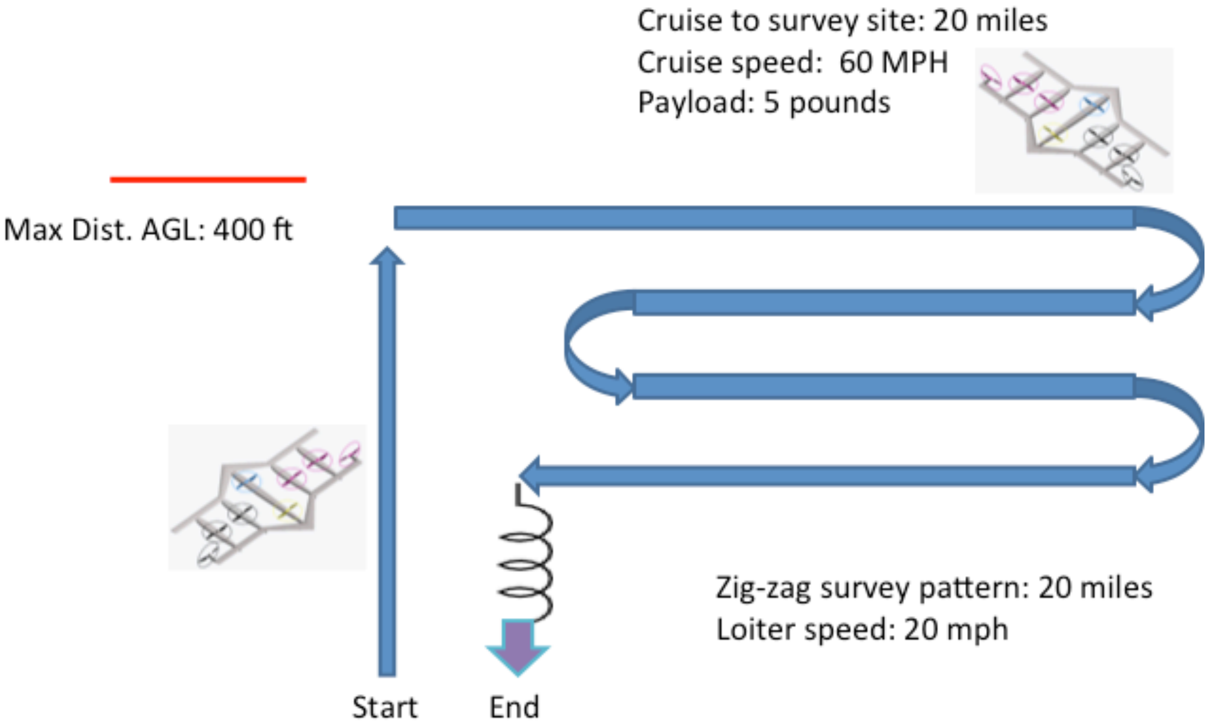


Figure 2. Search and rescue aerial survey as described in Ref. 12

Emerging missions and overall applications for uninhabited aerial vehicles are beginning to have a significant influence on vehicle design, particularly for small autonomous vertical lift aerial vehicles. Such aircraft no longer look like they are "scaled" versions of larger conventional aircraft but, instead, begin to evidence unique and innovative design attributes unlike those of pre-existing aircraft. Recent design trends such as that of all-electric and hybrid-electric propulsion, vehicle and network autonomy, the commercial availability of small low-power electronics and sensors, bio-inspiration, and robotics have also had a powerful influence on small autonomous vertical lift aerial vehicle design.

[†] Why SPRITES as an informal name/acronym for such vehicles? To summarize from various dictionaries/online sources: Sprites (red and blue) are high-altitude atmospheric electrical phenomena (thereby providing a tie-in with electric-propulsion and NASA research investigations); Sprites from folktales are winged, magical beings that are imbued with various levels of (usually mischievous) intelligence (thus providing a tie-in with UAVs and autonomous/intelligent systems); "sprite" and "spritely" also imply speed and agility, key attributes for emergency response missions.

It is the key proposition of this paper and associated earlier work that public service missions – particularly those related to disaster relief and emergency response – are perhaps, ultimately, the most consequential of all UAV applications. But the SPRITES concept is comprised of not only the vehicles, but the overall network, the dedicated ground infrastructure, and specialized robotic and teleoperated system payloads. Some of the key technical challenges for enabling DRER SPRITES missions are:

1. Development of low-cost commercial off the shelf (COTS) vehicles that are vertical takeoff and landing (VTOL) cruise efficient, easily flight controllable, can be configured with small MEPs (mission equipment packages) and cargo/payloads, and can support scalable network/autonomy capabilities;
2. Development of the Unmanned Aerial Systems Traffic Management (UTM; Refs. 27-28) or, alternatively, a precursor concept, "Inter-space" (Ref. 8) CONOPS and its realization;
3. Targeted network/connectivity concepts that can adapt to or support DRER missions;
4. Interfacing to complementary robotic systems and advanced mission equipment packages (MEPs);
5. Multi-system and multi-vehicle coordination;
6. Development of adaptable/resilient "robotic system-of-systems" for DRER missions rather than just consider UAVs only.

This paper is largely focused on the aerial vehicle but, in actuality, aircraft design is just one small element of the overall solution needed to satisfy the above technical challenges. Also important is, of course, the network development. A key underpinning of both the success of the aerial vehicles and network functioning is the incorporation of advanced automation and autonomous system technologies throughout all elements of this proposed complex "system of systems." In the case of vehicle autonomy, incorporation of onboard decision-making and not just remote operator control could positively impact the efficacy of the vehicle search. Examples of research into this type of autonomous search capability are noted, for example, in Refs. 3, 5, and 7.

Despite the necessity of advanced automation and autonomous system technology being incorporated into the SPRITES network to fully realize it potentiality, it is important to acknowledge that there might be initial public resistance. Such resistance stems, in part, from distrust in autonomous systems technology to date. Surmounting the current "chasm of distrust" related to vehicle/robotic autonomy, as represented graphically in Fig. 3, the following technical approaches are suggested:

A. Perform "design for safety" (minimize risk/hazard even if something goes wrong; rotor shrouds/ducts, rotor cages/lattices, multiple rotor graceful failure, frangible subsystems, airbags, parachutes, autorotation capability, remote failsafe control or "kill-switch" etc.; e.g. Ref. 8);
B. Utilize "systems analysis as applied to autonomy" (i.e. insure that only the right amount of autonomy is applied to the mission/application, e.g. Refs. 1-18);
C. Performing phased "shadowing" to establish acceptable autonomous system behavior (pilot in a box scored against pilot in the loop command and control);
D. Adoption of nondeterministic/stochastic success metrics and test and evaluation that are not underpinned by deterministic software testing/certification (e.g. UAV Turing-style tests, Ref. 16);
E. Early adoption/targeting of mission profiles that can be rigidly enforced/monitored (instead of on-demand point A to B flights rather adopt "freeways/railways" in the sky such as represented by "Hopper" aerial transportation system; e.g. Refs. 13-14);
F. Realizing cross-pollination of "search and avoid" and "autopilot" functionality technologies across their implementation between manned and unmanned vehicles;
G. Establishing public awareness registry of types of flights, owners and service providers, platforms, and frequency of "over-flights" over homes/business;
H. Defining "What's in it for me?" with respect to the general public and its acceptance of autonomous vehicles. This could entail the development of a notional trading market for overflights; e.g. to get a package delivery one has to "release" low-altitude "personal space" for other flights/missions for other customers/beneficiaries.

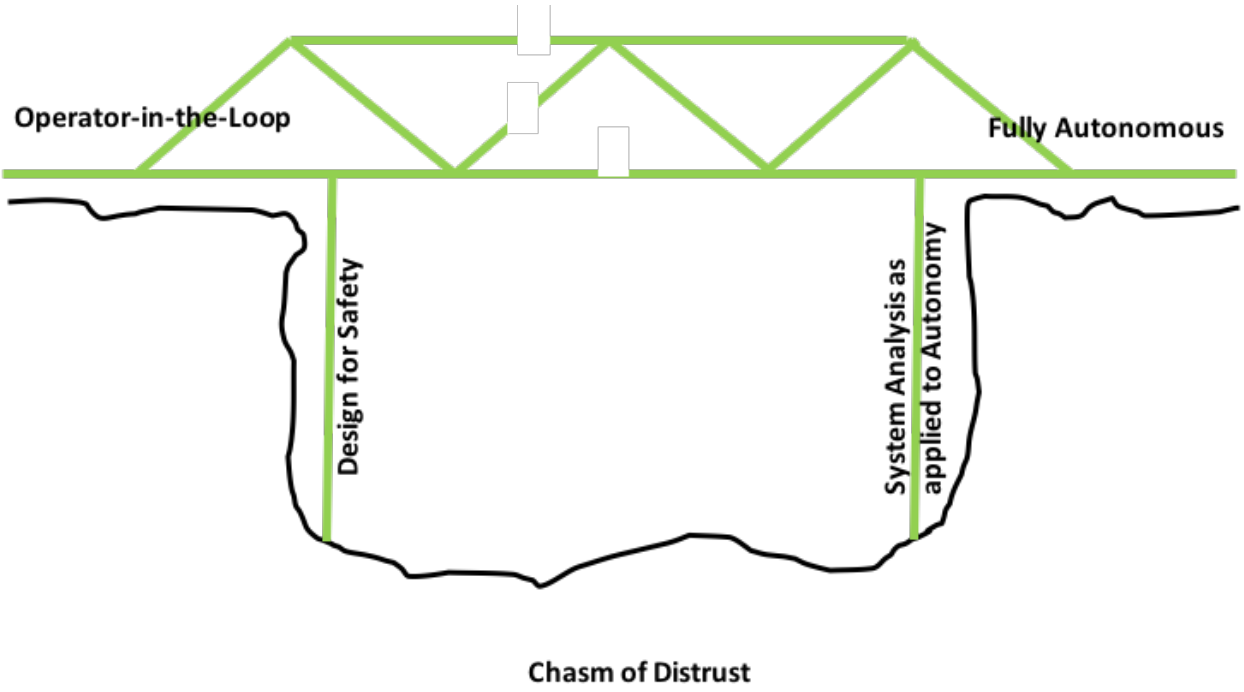


Figure 3. The "Chasm of Distrust" as to the public acceptance of autonomous system technology

A series of DRER mission storyboards will now be outlined. These storyboards will aid in helping elucidate SPRITES network notional requirements. The following are some representative DRER scenario/mission storyboards:

1. SAR in an urban/suburban environment. An elderly person suffering from dementia wanders from home and gets lost in an undeveloped, "green belt" area. Local police officers transport a small UAV in the back of their police cruiser. They set it up and deploy it on the edge of the green belt. After approximately a half-hour, imagery from the UAV guides officers on foot to approach and aid the elderly person.
2. SAR in a wilderness/rural environment. A hiker gets lost in a wilderness region. There is no cell phone connectivity, so the lost hiker cannot call for help. The hiker is lost in large area of over several hundred square kilometers. Family and friends alert first-responder agencies after two days of the hiker being out of contact. Truck/van-conveyed UAVs and support equipment are driven out to multiple points on the outskirts of the probable search area. Multiple simultaneous UAV sorties are conducted over the search area. The hiker is found by one of the UAVs. This UAV acts as a telecom relay to establish cell phone contact with the hiker. The hiker requests additional immediate aid. A small utility UAV is deployed to drop a first-aid kit and water to the hiker. This utility mission provides additional time so that rescuers can arrive by foot to escort out the hiker to a safe zone where helicopter extraction can be performed.
3. Localized (neighborhood) disasters: situational awareness and support. Outlying neighborhoods in a metropolitan area have been flooded. Longer range UAVs are used to provide a large-area initial assessment. Civilian and first-responder small UAVs are staged at various critical neighborhood locations. These small vehicles support dedicated local SAR missions to provide situational guidance for subsequent ground and air rescue by manned assets. A high altitude long-endurance UAVs are used as temporary telecom.
4. City-scale disasters: distributed relief. A major earthquake has struck a large metropolitan area. First responder assets including small autonomous SAR aerial vehicles perform initial surveys of the damaged areas. The imagery is transferred to network/cloud-based data analysis systems which prioritize first-responder neighborhood

response. An automated emergency call-for-action is sent out to volunteer commercial and civilian UAV operators as per a pre-existing DRER/UAV registry and pre-established aid agreements. Civilian and commercial UAVs begin coordinated operations with first-responder agencies to provide SAR and small aid package delivery to those in need. Disaster victims and relief requirements are established by smart-phone and digital device contact by the victims and/or automated relief assessment through network/cloud database analysis.

5. Major regional disasters: multi-wave surveillance and distributed relief. A hurricane makes landfall and devastates a large metropolitan region. Early first-responder support is provided by SAR UAVs (e.g. Refs. 21-22). The major regional airport has had operations suspended or severely by the aftereffects of the hurricane. Temporary large-scale landing zones have been established in key areas about the periphery of the metropolitan region. Supplies and aid from across the country are flown into the temporary landing zones by large VTOL/STOL aerial vehicles (e.g. tiltrotor aircraft as per notional CONOPS outlined in Ref. 11). Some of the aid is transported to key local/neighborhood facilities and/or directly to victims by means of "delivery drones" (and delivery drone infrastructure, e.g. Ref. 15) commandeered via the network/cloud-enabled vehicle registry and coordination automation. Pre-disaster evacuation and post-disaster personnel and equipment transportation are enabled by commandeering the metropolitan region's "Hopper" aerial mass transport system (e.g. Refs. 13-14 and 23).

6. "Impossible" missions: Mt. Everest pinnacle rescue, etc. A mountain climber suffers life-threatening altitude sickness. Additionally, a severe weather system is approaching the climber base camp. A small high-altitude-compatible UAV is dispatched to deliver medical supplies and a teleoperated medical diagnostic system to the climber base camp to aid the ill climber. A large autonomous aerial vehicle acts as a carrier platform for an autonomous tracked ground vehicle. The large aerial vehicle lands at a site at a lower elevation to the base camp and releases the automated tracked ground vehicle. The tracked vehicle advances up the mountain and arrives at the base camp where the ill climber has been receiving onsite treatment supported remotely through the teleoperated medical equipment. The ill climber is placed on a stretcher in the tracked ground vehicle which, subsequently, returns to the large aerial vehicle. The ill climber is then transported to a medical facility off the mountain.

The above storyboards represent a spectrum of SPRITES network capabilities required to ideally support a wide-range of DRER missions. Figure 4 illustrates the qualitative trend of SPRITES technology capability with respect to being able to quickly respond to individual emergencies.

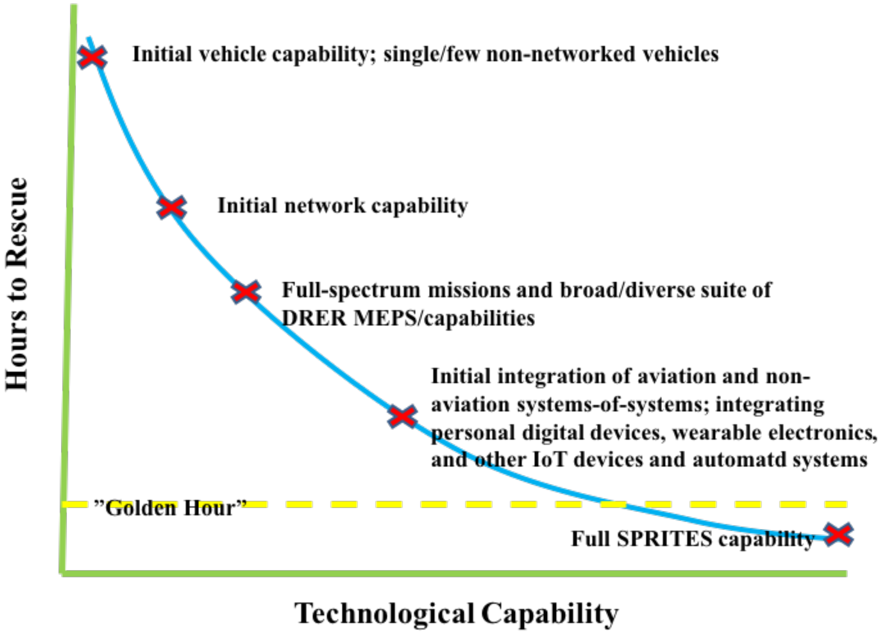


Figure 4. Notional Reduction in "Hours to Rescue" as an inverse function of Technological Capability

II. SPRITES: Vehicles and Networks

As noted before the overall SPRITES concept is both a set of network concepts and a set of vehicle concepts. A single vehicle, in and of itself, is unlikely to greatly enhance capabilities to a given SAR or DRER mission. It is only through a network of multiple platforms that significant advancements in mission capabilities can be achieved. Accordingly, not only do the functional attributes of SPRITES vehicles have been carefully defined and designed into the platforms but the whole SPRITES network (and how it interacts with external or non-SPRITES systems) needs equal attention.

Figure 5 is a closer examination of the SAR SPRITES mission. Two SPRITES vehicle/network drivers are obvious for SAR missions: speed is essential and the more vehicles and searchers the better (as long as they can be satisfactorily coordinated so as to maximize the area surveyed, maximize the quality/rigor of the search, and non-interfere with both aerial and non-aviation assets). Figure 5a schematically represents methodical stepwise coverage of a search area. Figure 5b is a more "organic" aggregate of searches comprising the overall search area. Figure 5b is probably more representative of search pattern that, though coordinated, employs multiple vehicles and operators; inherent is the assumption that these vehicles are deployed at sites constrained by operator ground access thus negating a full coverage search.

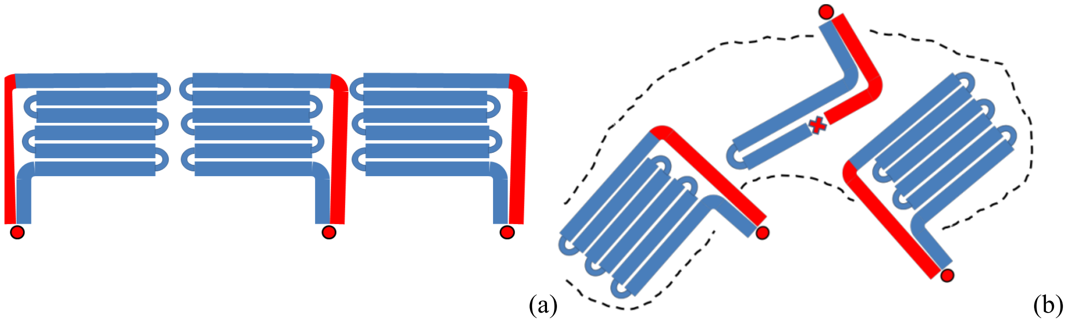


Figure 5. Search and rescue: (a) methodical and (b) or "organic" with multiple vehicles (but still coordinated)

The following simplified model is used to define the qualitative trends summarized in Figs. 5-7: $V = f(L/D_e) \approx a_V + b_V\, L/D_e$ where in this particular analysis it is assumed that $a_V = 5$ and $b_V = 10$; $GW = g(V) \approx a_{GW} + b_{GW}V$ where in this particular analysis it is assumed that $a_{GW} = 1$ and $b_{GW} = 0.4$; the battery mass is expressed as a simple fraction of the vehicle gross weight, $m_{Bat} = \epsilon GW$ where it is assumed that $\epsilon = 0.2$; the visible lateral sensor view from the vehicle track is $\pm 100m$; the battery energy density is assumed to be a conservative 150 W-hr/kg; finally, the power required for takeoff and landing and hover is neglected in this first-order analysis. This simplified model assumes that as vehicle lift-to-drag ratio is improved then vehicle gross weight will increase (to reflect a more robust capability vehicle) and speed will improve.

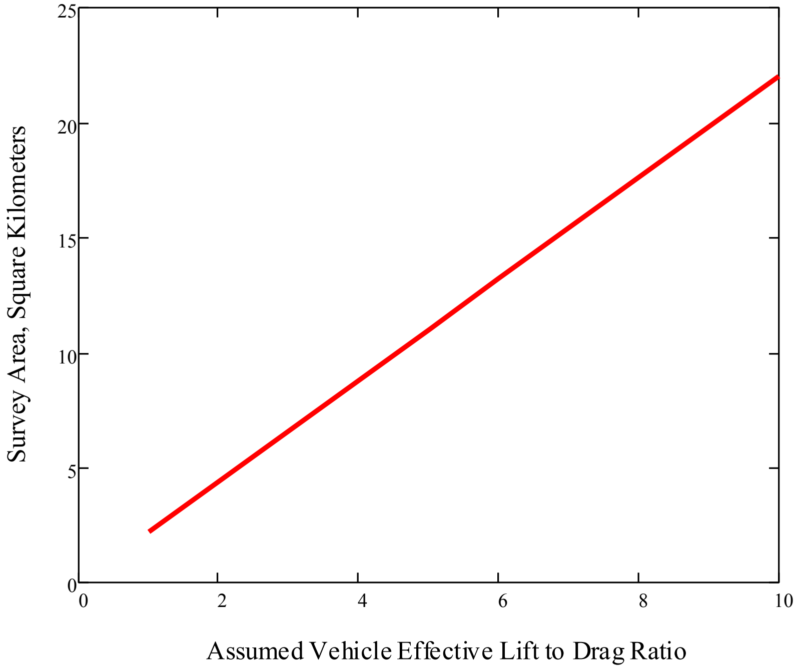


Figure 6. Area surveyed as a function of vehicle aeroperformance (primarily driven by Lift-to-Drag Ratio)

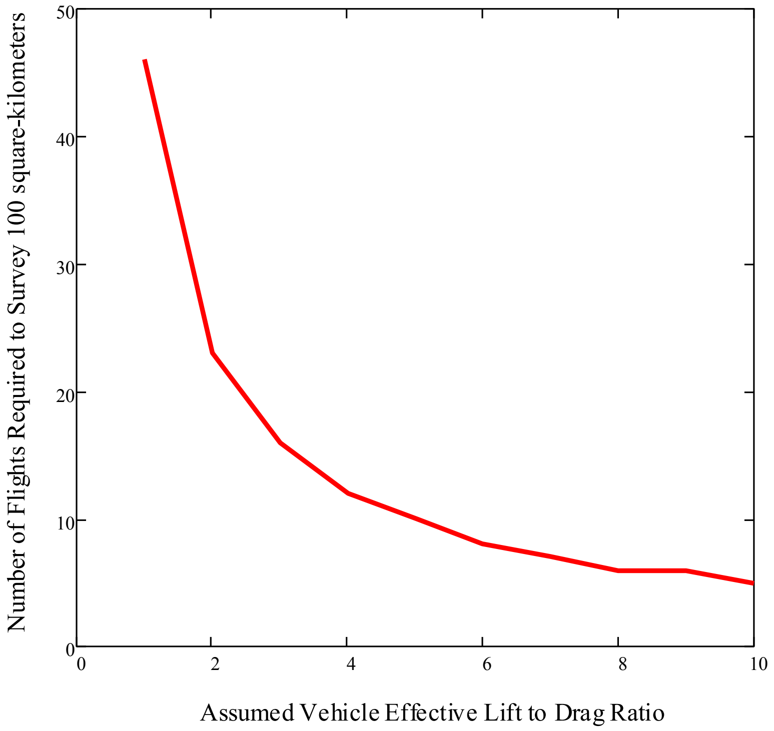


Figure 7. Number of flights required to survey a 100 square-kilometer as a function of vehicle aeroperformance

Figures 7-8 clearly show both the power of employing a network of multiple vehicles to conduct a SAR aerial survey as well as maximizing the aeroperformance of the individual aerial vehicles. To survey a hundred square-kilometers with a single hour, the so-called "golden hour" in which the greatest number of lives might be saved, requires nearly fifteen or more vehicles having effective lift-to-drag ratios representative of the typical quadcopter or multirotor configuration currently commercially available. More capable and larger vehicles can significantly reduce the number of vehicles required to meet the "golden hour" requirement. Reducing on-ground time between flights would have a significant second-order effect on meeting the golden hour requirement. Survey area coverage, though, is only one small part of the overall SAR problem. The vehicles will have to be capable of carrying, powering, data capturing/storing, and potentially transmitting high-bandwidth multispectral data for onsite and remote consumption/analysis. This points again towards the need for a network of large, high aeroperformance capable vehicles that have to be relatively low-cost and readily available to local first-responders. There are some significant challenges to realistically meeting these challenges.

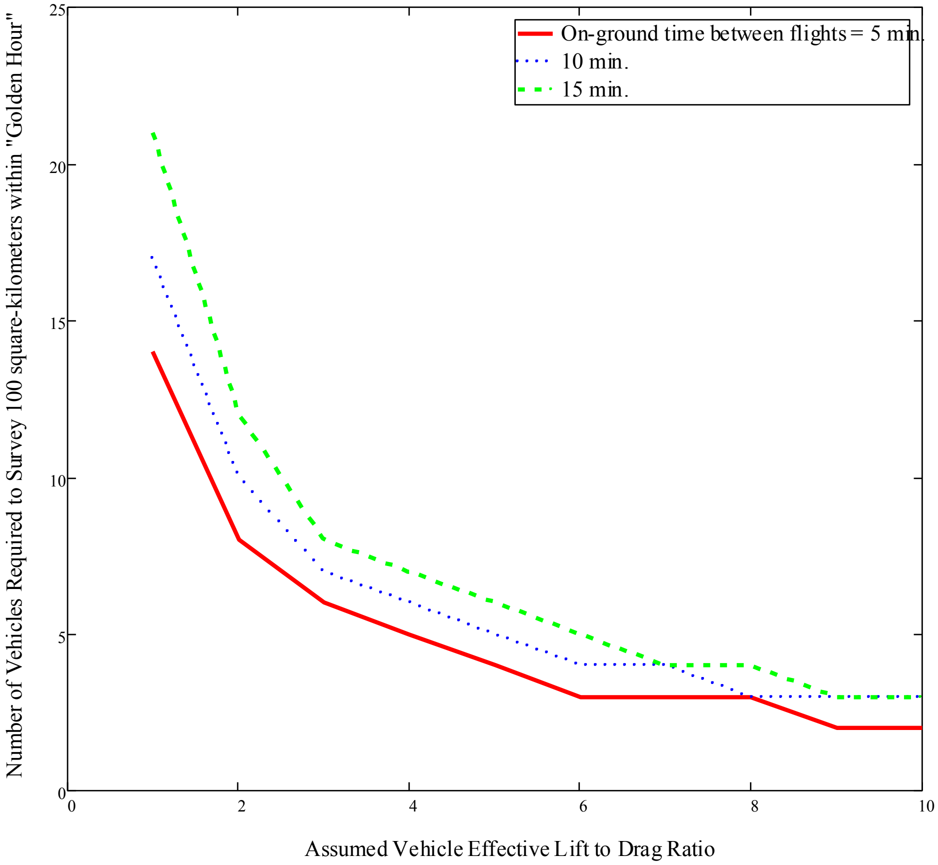


Figure 8. Number of vehicles required to survey a hundred square-kilometer under the "golden hour" time requirement

The SAR problem becomes significantly compounded if the search is in a large, forested, rugged-terrain, wilderness search area. Longer range and higher endurance vehicles become more necessary for the search. Adoption of more sophisticated sensors, as well as more sophisticate autonomous search software, also becomes more desirable. Nonetheless, analogous to field science campaigns discussed in Refs. 3-7, 19, 42, there are interesting open questions as to the employment of the many simple small (MSS) versus the few complex large (FCL) aerial vehicles for searches.

Figure 9 is a high-level examination of the small disaster relief utility SPRITES mission. Three different utility deployment models are suggested in Fig. 9. (This is hardly exhaustive, other utility deployment models could be proposed.) The small disaster relief utility mission is fundamentally different from the SAR mission. The emphasis for the aerial vehicles for the SAR mission is on the searching of a survey area; rescue, in turn, would be performed by first responders on the ground or using their manned aerial assets. The utility mission, though, is focused on rapid, targeted, delivery of critical aid in form of small packages/payloads. Such small aid packages/payloads could be anything from medicine and first aid kits, to emergency supplies such as water and food, all the way to sophisticated tele-operated/tele-monitored medical and rescue devices and equipment (e.g. Ref. 10). Additional aid (of larger volume/mass) is, of course, to be expected to be provided somewhat later by ground assets and larger and/or manned aerial assets; small UAV assets such as that proposed for the SPRITES network can only be considered the first-wave of aid and not a comprehensive DRER solution.

In implementing utility SPRITES missions a number of aid deployment models might be considered. Figure 9a-c illustrates three different models that could be employed in the aid package delivery approach.

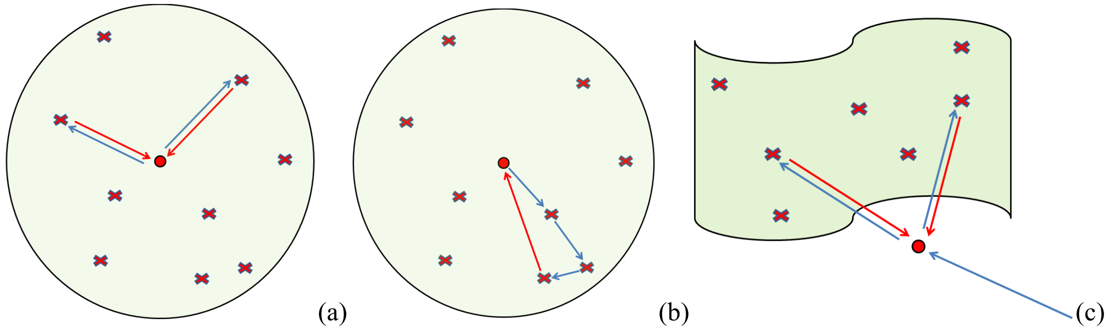


Figure 9. Small disaster relief utility missions: (a) one-package/one-delivery/one-depot model, (b) multi-package/delivery but one depot model, and (c) one-package/one-delivery/remote/temporary depot model

Figures 10-11 provides a simple small aid package delivery analysis consistent with the DRER utility mission shown in Fig. 9b. It leverages off of the simple vehicle model employed in the earlier search and rescue analysis.

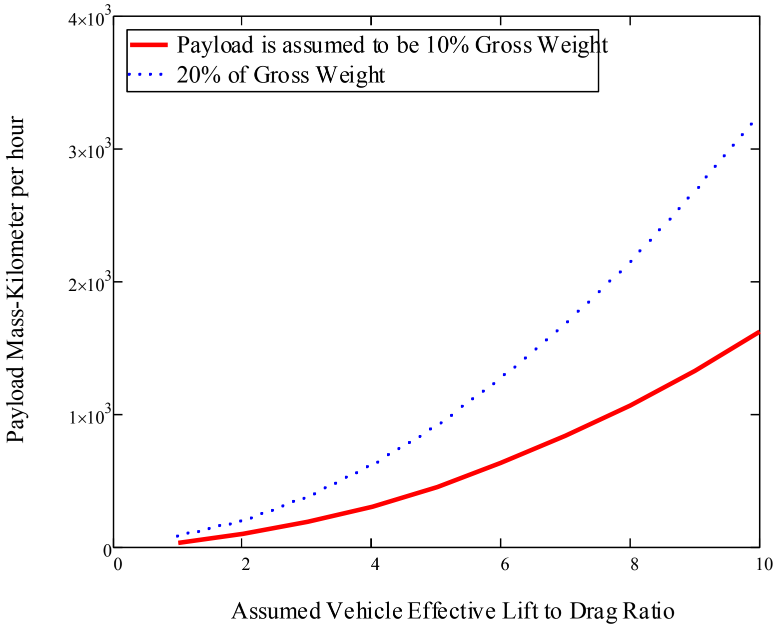


Figure 10. Payload distribution efficiency in terms of kilogram-kilometers per hour as a function of assumed aerial vehicles' effective lift-to-drag ratio and payload mass fraction

Figure 11 provides a simple analysis of the number of flight sorties required to distribute a finite number (in this particular case, a thousand) of aid package deliveries as a function of the aerial vehicle assumed effective lift-to-drag ratio and total payload mass fraction. As anticipated, the greater than vehicle aeroperformance efficiency (higher effective lift-to-drag ratio), the fewer flight sorties are required to distribute the total number of aid packages. Correspondingly, also as expected, a greater payload capacity to the vehicles (in the form of a higher total payload mass fraction for the vehicle), the fewer the flight sorties required.

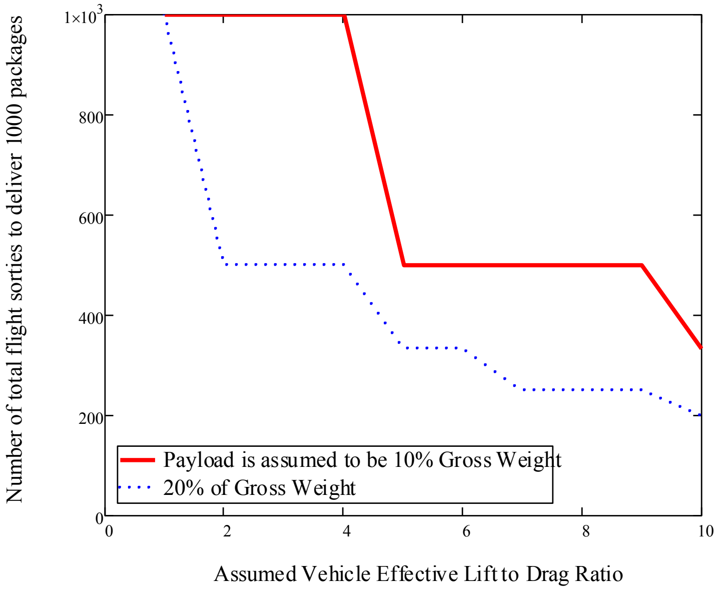


Figure 11. Number of flight sorties required to distribute one-thousand aid packages (2 kg per package and one package per flight-leg in the overall sortie) as a function of vehicle effective lift-to-drag ratio and total payload mass fraction

It is assumed in Fig. 11 that the average distance between package deliveries is five kilometers and that the average aid package mass is 2 kg. The same simplified models for vehicle gross weight and cruise speed as a function of assumed effective lift-to-drag ratio were used in deriving the utility mission results of Figs. 10-11 as were used in the search and rescue mission results for Figs. 6-8.

The above results – Figs. 10-11 – substantiate the same general conclusions for utility missions as was evidenced for the search and rescue missions: that there is considerable value to these missions in increasing vehicle size, total payload mass fraction, and overall aeroperformance efficiency.

A. SPRITES Networks in Small and Large Emergencies, Wilderness versus Urban Environments, and Near- and Far-Future Implementations

The efficient conduct of SAR and DRER missions are not solely a wilderness or rural problem, nor are they primarily an urban or suburban problem. Both global sets of environments need to be considered in the notional development of SPRITES systems. One of the biggest implications of conducting DRER missions in wilderness versus urban environments is the relative magnitude of connectivity between the various assets/systems deployed/employed for those missions. Figure 12 illustrates the implications of connectivity on some of the notional DRER autonomous aerial vehicle concepts being proposed. The engineering community is slowly embracing an IoT (Internet of Things) or IoE (Internet of Everything) philosophy for future connected devices. This philosophy is already starting to be incorporated into uninhabited aerial vehicles, aka "drones" (e.g. Ref. 24).

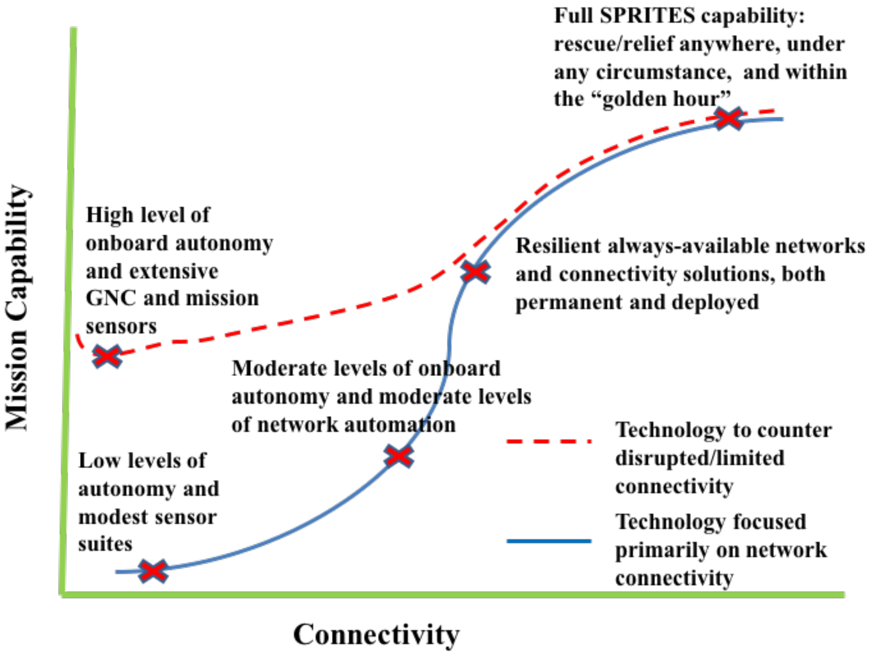


Figure 12. Connectivity and SPRITES mission capability

Some of the more far-term future missions and implements of the SPRITES networks could be based on some of the concepts outlined in Ref. 22.

B. SPRITES Networks and Airspace Integration

In the future SPRITES networks can be modeled in simulations (with Discrete Event Simulation software) for a wide variety of DRER missions and operational scenarios. This modeling could be based off of similar simulations such as Refs. 12, 14, and 15.

It is highly likely that future airspace will be filled with an extremely large and diverse number of aerial vehicle platforms (manned, unmanned, VTOL, etc.). This will require high-bandwidth interaction between ground and airborne systems for trajectory updates and continuous contingency management. Current aviation research is generally stove-piped with respect to focusing on certain vehicles classes, missions, and interactions – which is inadequate. Autonomy in the airspace will provide a level of service individually tailored to diverse aircraft types that allows them to interact safely and efficiently. SPRITES networks will require a paradigm shift in aerial vehicle onboard autonomy and autonomous interactions with ground, UAV Traffic Management (UTM), and ATM assets/systems.

In the context of a SPRITES mission, the following holds: a future, highly-complex environment with both drones and manned operations wherein an emergency situation requires high priority surveillance and urban aid package delivery operations which, in turn, necessitates complex negotiations between UTM system, air traffic control, and all types of aircraft.

It is anticipated in the suburban/urban environment that there will be several different tiers of “vertiports” in the context of the SPRITES networks:

1. Unprepared landing zones;
2. Ground/mobile transport and support (from police cars, manned or unmanned “carrier” aircraft (e.g. Ref. 22), etc.);
3. Small “mail box”/kiosk vertiports for neighborhoods;
4. Small commercial/civil vertiports (<4 vehicles at a time);
5. Midsize commercial/civil vertiports (<10 vehicles at a time, e.g. on commercial building rooftops);
6. Mid to large public “metro station” vertiports (e.g. “Hopper” stations, Ref. 13);
7. Large logistic centers (e.g. as proposed for large-scale commercial “delivery drones”).

Note that in the above list it is not proposed that small UAV vertiports be integrated with existing large commercial aircraft airports. The reasoning for this is an attempt to minimize airspace integration issues.

C. SPRITES Integration with Autonomous and Robotic System-of-Systems

The SPRITES concept can be considered a subset of the vehicles and robotic DRER systems summarized in Refs. 1-2 and 9-11. What makes the SPRITES unique with respect to some of these other DRER vehicle and systems concepts is the emphasis in this paper on surfacing cross-cutting synergism between commercial “drone” missions such as commercial package delivery and public-service aid package delivery during large-scale disasters and smaller scale emergencies. This cross-cutting synergism could be of many forms. In one ideal sense the commercial delivery drones could be intentionally developed so as to be able to intrinsically support DRER missions in a dual-use design sense and, further, such commercial delivery drones could be rapidly pressed into DRER service (through some sort of regulatory and networking approach) upon grave need. Similarly search and rescue missions might be supported upon grave need by civilian, consumer/hobbyist drones if, again, some sort of appropriate and robust regulatory and networking approach could be devised.

Another important consideration in the overall SPRITES concept is the overall level of autonomy and intelligence onboard the vehicle versus that hosted in the network, ostensibly in the “Cloud” (e.g. Refs. 25-26). This assessment can be, in part, leveraged off of ‘systems analysis as applied to autonomy’ concepts introduced in Refs. 17-21.

There are six areas of autonomous system technology that need to be developed to fully realize the SPRITES network concept:

1. Interfacing to the traditional air traffic management system;
2. Interfacing to traditional first-responder and disaster relief agencies’ alert and command and control networks;
3. Onboard vehicle autonomy, especially with respect to flight mission plan decision making and data gathering to optimize in-flight response;
4. Cloud and internet of things (IoT) autonomy to create a unique command and control and DRER database for disaster and emergency response, especially as arriving at collective, distributed means of responding to disasters as well as collectively sharing and analyzing data gathered;
5. Automated interfacing and integration of automated and non-automated support and ground-infrastructure to support a very large number of aerial assets for large-scale disaster response (i.e. vertiports, hospitals with semi-automated distribution of medical supplies and teleoperated devices, FEMA, National Guard, and community emergency supply depots that can support small autonomous aerial vehicle assets, etc.);
6. Teleoperated and semi-autonomous devices and robotic systems that can be deployed and controlled by small autonomous aerial assets to provide critical “golden hour” first response support to not only first-responder professionals but to the general civilian population to maximize the likelihood of life-saving (i.e. defibrillators, epi-pens, first-aid/trauma kits, small oxygen supply tanks, ground search robots, etc.).

Some of the SPRITES autonomy requirements include: maintain separation from other aircraft and obstacles/ground; safely operate in low-altitude urban environments and in the first/last 50ft; re-planning and negotiation with airspace management and other aircraft for resources and desired trajectories; vehicle health monitoring; contingency management in case of mechanical failure, lost-link, or UTM directive; payload loading/unloading.

References 3-7 discussed in considerable detail some onboard autonomy challenges inherent in search and rescue missions (through discussion related to analogous aerial science investigation campaigns). In much of this past work, a bio-inspired set of search behaviors was advocated. High levels of onboard autonomy will still be required for UAVs supporting DRER missions even in the case of high-levels of network connectivity being theoretically available to support the vehicles and their missions. After all, unfortunately, network connectivity might be severely degraded in large-scale, extreme disasters.

Finally, though the focus for this paper is on smaller vehicles that can perform search and rescue or small aid package delivery utility missions, there is a much greater autonomous vertical lift aerial vehicle design space for DRER missions that could be considered (e.g. Refs. 1-2 and 8-10). Specifically, as one example, "Hopper" networks, as described in Refs. 14-15 and 24, could be used to mobilize mass evacuations in urban environments; further, such notional Hopper networks could be leveraged by regional relief tiltrotor-enabled efforts such as described in Ref. 12.

D. Notional SPRITES Networks Technology Roadmaps, Critical Demonstrations, and Implementation

If it is indeed essential that a large number of very capable uninhabited aerial vehicles are readily available upon immediate demand to support local/regional first-responders in responding to emergencies – with an attendant sophisticated ground-based infrastructure required -- then it is also essential to consider the non-technological implications of SPRITES networks. Among those considerations is the proposal of economically viable business models that might make such networks possible. Possible SPRITES business models to establish a robust UAV DRER mission capability:

1. First-responder/local-government-centric: single use SAR and multi-use SAR and policing;
2. Deployable regional/national first-responder;
3. CRAF-like (civil reserve air fleet) UAV fleet for domestic DRER missions (civilian fleet that is subsidized by the government so as to be redirected upon need for emergencies);
4. Volunteer fleet (levels of access/support on the basis of equipage and platform capability and autonomy);
5. Draft/commandeer (on demand control of civil platforms via network coordination and command; two-tiered levels of command and control, i.e. civil and emergency; note that there are inherent cybersecurity issues to address with this approach);
6. Online/real-time service bidding;
7. On-demand, rapid/additive manufacturing/production of customized systems (the "fifteen-minute UAV");
8. Sentinel systems (automated hanger/storage units for release/deployment of vehicles, i.e. consistent with the "fire spotter" concept of the past and/or moribund vehicles awaiting activation and initiating mission sorties; Ref. 9);
9. Tractor-trailer and aircraft carriers to transport and deploy pre-staged swarms of vehicles in "aviaries" (would include "aerial surveyor" and "fractal flyer" concepts, e.g. Refs. 21-22);
10. Deployable "seeds" and bio-manufactories to manufacturer on-demand UAVs from bio-feedstock on the ground and in the disaster area (e.g. Ref. 34);
11. World-wide rapid response (with lifting-body reentry vehicle rotary-wing-decelerator/auto-gyro work, Ref. 31).

Some of the immediate NASA research gaps that should ideally be addressed for the realization of SPRITES, "delivery drones," urban air mobility systems, are as follows etc.:

1. Advanced airspace tools need to be developed. Especially advanced tools to take conceptual/preliminary aircraft design code output and craft input/models for advanced aircraft to be modeled in ACES (e.g. Ref. 39) and FACET (e.g. Ref. 40), or similar, tools.
2. Need to develop specialized local/regional airspace simulation tools for passenger-carrying VTOL aircraft and low-altitude/urban operating environment vertical lift and fixed-wing short takeoff and landing or conventional takeoff and landing (STOL /CTOL) UAVs. This would include the modeling of vertiports or ground/base stations as unique airspace traffic management constraints. Some limited experience developing the "BaySim" tool (originally developed for the "Hopper" study of electric public transport type helicopters in the Bay Area, Refs. 13-14 and 23) and integrating results with FACET predictions of conventional traffic but more work in this area for a broader range of vehicles and mission scenarios is required.
3. Need to develop system-of-systems analysis tools and study perspective to effectively model emerging VTOL and vertical lift UAV transportation networks. Such system-of-systems tools would be capable of conceptually designing, simulating, and operationally analyzing not only the aircraft but the complete network of autonomous and non-autonomous systems necessary to sustain the notional transportation network. For example, a limited cradle-to-grave analysis of the "Hopper" electric public transport helicopter network (Ref. 13) identified the potential hazardous solid-waste management issues inherent in a large number of expended large batteries that might result for an all-electric, battery-powered fleet.
4. Consider the development of vehicle conceptual design tools that incorporate nontraditional aircraft design constraints into UAV design: protective shrouds, automated package deployment devices, laser sensor networks to cutoff of electric motor and perhaps actively brake if person/animal gets too close to a vehicle, new rotor disk loading design criteria to avoid rotor downwash/outwash flattening flower beds, etc.
5. Consider developing "extreme event" airspace modeling tools to assess schema for building maximal resiliency into the beyond-NextGen NAS (national airspace system) – both to support potential emergency response and disaster relief efforts as well as preserving as much normalcy for the majority of air traffic as possible under extreme events.
6. Need updated aircraft emissions and noise tools for VTOL UAVs that can be seamlessly integrated with local/regional and NAS-wide airspace simulation tools.
7. Consider the development of a series of demonstrations, i.e. should consider setting up a simulated "drone delivery" network at a NASA center to evaluate enabling technologies. Alternatively, a series of public service emergency response and/or disaster relief demonstrations could be conducted to assess enabling airspace, operations, and vehicle technologies.
8. It is unclear how "trusted" autonomy and/or "V&V for nondeterministic systems" is ultimately to be achieved. One approach, that may or may not be worth considering, is the development of a "shadowing" – i.e. where a standalone pilot-in-a-box (PIB) can be non-intrusively incorporated into manned aircraft cockpits such that the PIB predicted (but not implemented) next step piloting performance can be tracked/compared to the human pilot actual next step control inputs. With the advent of electronic flight-bags such a shadow/PIB might be feasible. Additionally, if such a system were adopted in a widespread and sustained manner a database of hundreds to thousands of flights on hundreds of flights under real operational scenarios could be acquired. Such a shadow/PIB system approach could be applied to other autonomous system applications that seek to (partially) substitute human operators with intelligent systems; therefore there could be considerable potential for technology transfer across multiple industry sectors.
9. Finally, there is a need to develop system analysis tools for autonomy that place autonomous system technology issues squarely into the vehicle conceptual/preliminary design process.

III. Some Fundamental Aerodynamics Considerations

There are several interesting rotor/lifting-surface interactional aerodynamics questions and challenges raised by the two notional RED and BLUE SPRITES vehicle concepts. First, is there an optimal arrangement of arrays of lifting rotors? Can aeroperformance efficient closely-coupled tandem-wing configurations be developed for small UAVs? Can such closely coupled tandem-wing geometries be tailored so as to effectively "shroud" the lifting-rotors and propulsors to mutually protect the rotors and propellers from collision with objects and people? Can structurally robust multi-lifting-surface wing geometries be achieved by incorporating joined- or braced-wings as a tradeoff between high thickness ratio wing airfoils? Finally, is there a potential aeroperformance efficiency benefit to slowing – and possibly stopping – the rpm of the lifting-rotors at higher vehicle cruise speeds? And, further, if the lifting-rotors were slowed while at higher forward-flight speeds, how would the incorporation of flaps/flaperons on the aft wing (or aft lifting-surfaces) complicate the interactional aerodynamics of the total system in providing for stable static trim of the overall vehicle?

Reference 12 was one of the more recent attempts to quantitatively examine the question of whether or not there was an optimal arrangement of arrays of lifting rotors for distributed multirotor configurations. Classical rotor theory (e.g. Ref. 37) would suggest that a series of side-by-side rotors would see an increase aero efficiency with increasing number of rotors, such that the span loading of the rotors would approach that of a high aspect ratio wing, in its extreme. The results from Ref. 12 were somewhat more mixed in that only spanwise arrays of fixed-pitch propellers were employed as lifting-rotors. As such, the disk loading distribution was far from being the ideal uniform loading of classic theory. Consequently, the "spanwise" rotor-array lift distributions was also far from being uniform and, so, the classic theory's predicted reduction in induced drag/power was not achieved. It is, accordingly, an open design question as to whether fixed-pitch propellers can be used as aero efficient high-speed lifting-rotors. Instead, it might be necessary to slow or stop the lifting-rotors at relatively low forward-flight speeds or, alternatively, fixed-pitch propellers will need to be replaced with flapping rotors with collective and cyclic pitch control.

Closely-coupled tandem-wings are proposed for the vehicle configurations studied in this paper not because they are anticipated to be more aeroperformance efficient than conventional mono-wings but, instead, because they offer an approach to "shroud" or protect people and objects from impact with spinning rotor blades as well as, perhaps, an opportunity to act a lightweight truss-like structures providing an efficient approach to high bending and torsion stiffness lifting-surfaces. There is a considerable body of research into tandem-wings, both classic and recent (e.g. Refs. 40-41). There are two unique aspects of the tandem-wing geometries studied in this paper. First, the spacing between the forward and aft wings is quite close to each other, i.e. on the order of 1c to 2c. Second, the interactional aerodynamics of the joined- or braced-wing configurations studies encompass not only wing-on-wing interactions but wing-on-rotor and rotor-on-wing interactions (adding to the complexity of the overall problem is the rotor-on-rotor interactions noted earlier).

Joined- and braced-wing vehicle configurations have over the past decade gained a modest resurgence in interest from the research community. The bulk of these joined- or braced-wing vehicle configurations have been proposed for efficient cruise subsonic commercial transport aircraft but joined-wing vehicle configurations have also been considered in the past for VTOL – particularly tiltrotor – aircraft. Joined-wing VTOL UAVs have recently begun to be proposed for delivery drones and urban air mobility vehicles. It is currently an open question as to whether joined-wings versus thicker wing airfoil sections are the preferred approach for the notional RED and BLUE SPRITES vehicles to arrive at structurally robust and stiff aggregate wing structures.

Finally, the global question of incorporating slowed- or stopped-rotors into the vehicle design is not considered in any significant depth in this current paper. Nor is the interactional aerodynamics of flaps/flaperons for closely-coupled tandem-wings considered. It is likely, though, that such a capability would be desirable for higher speed vehicles.

The primary aerodynamic question examined in this paper was the interactional aerodynamics of closely-coupled tandem-wings. This was examined by means of the use of CFD and is only a preliminary investigation. The computational fluid dynamics (CFD) software "RotCFD" was used to examine some of these aerodynamic questions (Ref. 30). As an initial effort, the question of what is the effect of the tandem wing geometries on the net lift characteristics of the vehicle's wings was considered; refer to Figs. 13-16; for recent tandem-wing research, see Refs. 40-41.

The predicted surface pressure distributions for a single wing are presented in Fig. 13. The wing is a constant chord, NACA 0012 airfoil section. The chord length Reynolds number is ~500,000. The predictions use the "realizable k-e" turbulence model in RotCFD. Thicker airfoils (NACA 2424 and 4424) were used in later iterations of the design effort but the below results for the wing with the NACA 0012 airfoil section are still anticipated to be generally applicable to the overall close-coupled tandem-wing interactional aerodynamics problem.

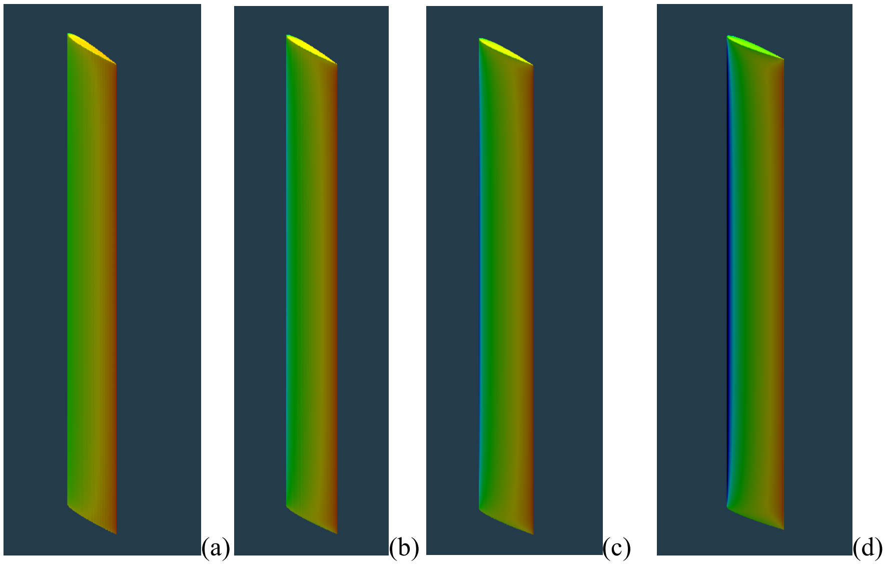


Figure 13. Representative isolated wing (upper) surface pressure distribution predictions: (a) AOA = 3 deg.; (b) AOA = 6 deg.; (c) AOA = 10 deg.; (d) AOA = 15 deg.

As can be seen in Fig. 14, surface pressure distribution predictions are presented for the forward wing at an angle-of-attack of 3 deg. Correspondingly, Fig. 15 presents the tandem wing surface pressure distributions for a forward wing angle-of-attack of 6 deg. In both cases, the wings are not swept and have a wing aspect ratio of ten; the wings were constant chord, untwisted, and used NACA 0012 airfoils.

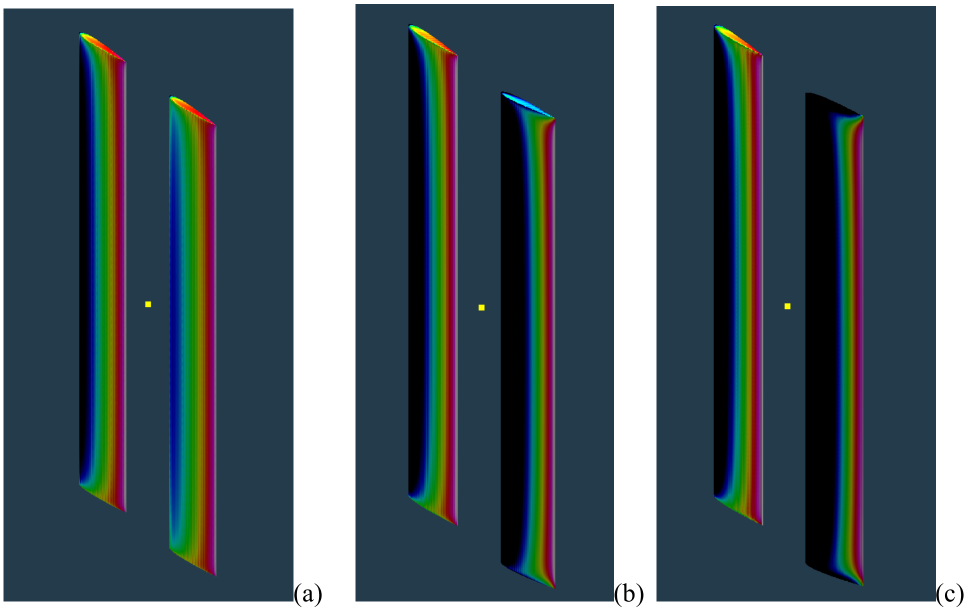


Figure 14. Representative tandem wing surface pressure distribution predictions (AOA forward wing = 3 deg.) (different scale as from Fig.13 but the same as that of Fig. 15): (a) AOA aft wing = 3 deg.; (b) AOA aft = 10 deg.; (c) AOA aft = 15 deg.

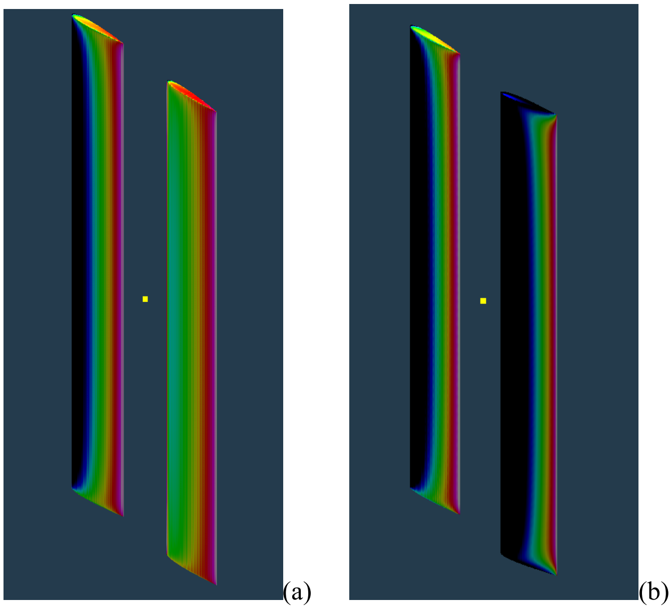
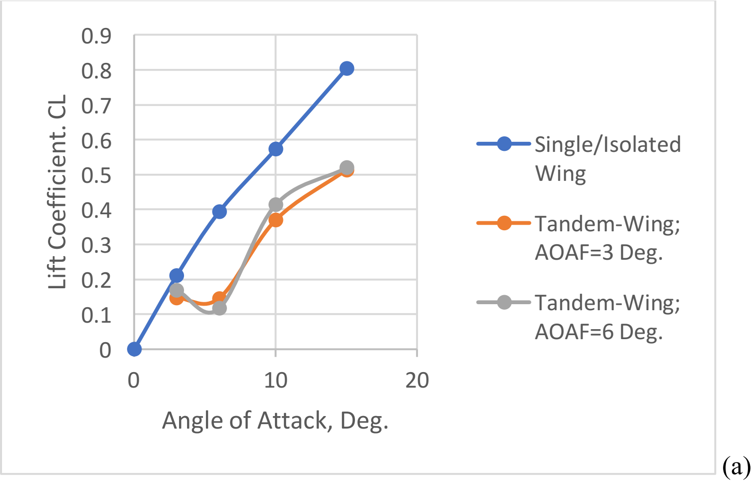
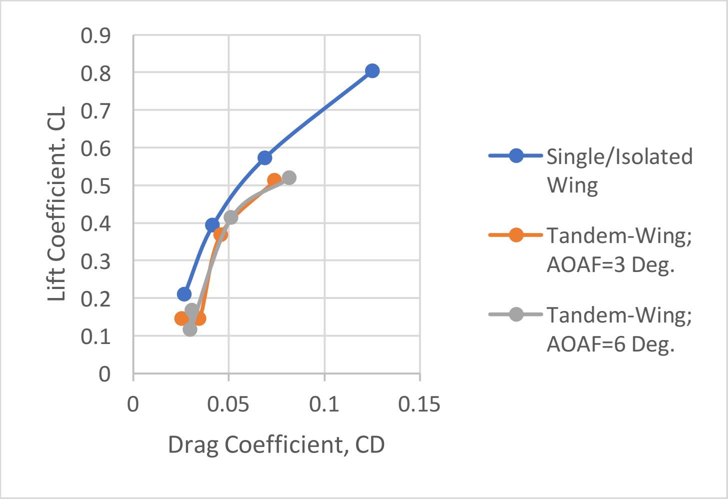


Figure 15. Representative tandem wing (upper) surface pressure distribution predictions (AOA forward wing = 6 deg.): (a) AOA aft wing = 3 deg.; (b) AOA aft = 15 deg.

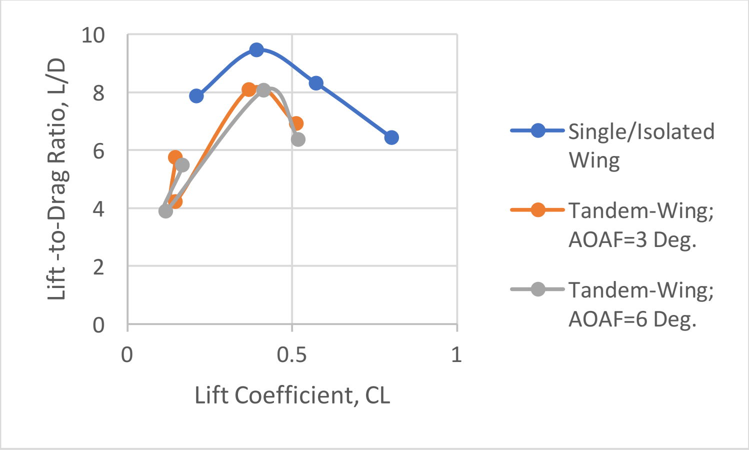
Figure 16a-e is a series of results illustrating the wing-on-rotor aerodynamic interference effects predicted by the initial tandem-wing CFD work. For the tandem-wing geometry studied there is clearly a negative effect of both lift and drag for the closely tandem-wings as compared to a single isolated wing.





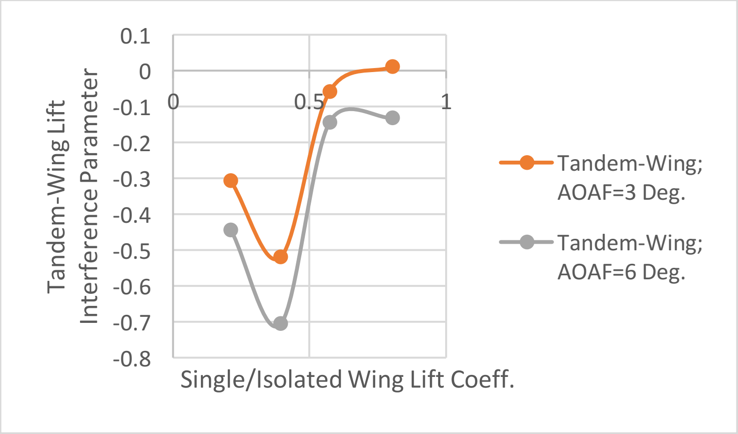
Lift Coefficient. CL
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.05
0.1
0.15
Drag Coefficient, CD
Single/Isolated Wing
Tandem-Wing; AOAF=3 Deg.
Tandem-Wing; AOAF=6 Deg.

(b)



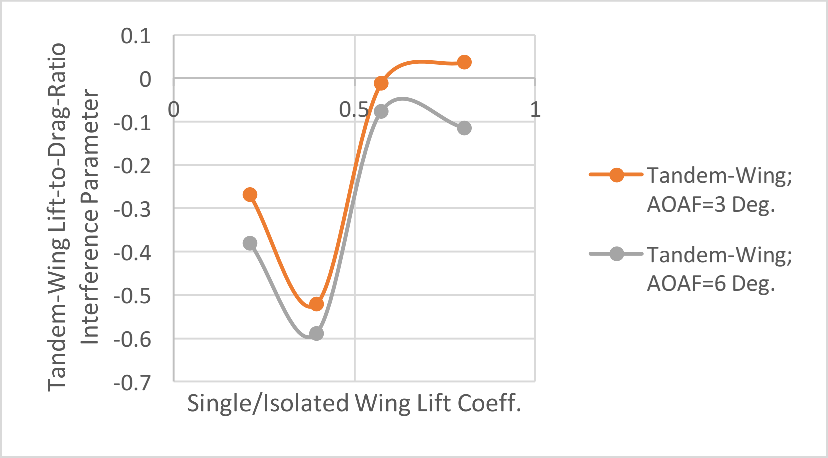
Lift -to-Drag Ratio, L/D
10
8
6
4
2
0
0
0.5
1
Lift Coefficient, CL
Single/Isolated Wing
Tandem-Wing; AOAF=3 Deg.
Tandem-Wing; AOAF=6 Deg.

(c)



Tandem-Wing Lift Interference Parameter
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
0
0.5
1
Single/Isolated Wing Lift Coeff.
Tandem-Wing; AOAF=3 Deg.
Tandem-Wing; AOAF=6 Deg.

(d)



(e)

Figure 16. Effect of tandem-wing wing-on-wing interactions: (a) lift curves, (b) drag polars, (c) lift-to-drag ratios, (d) tandem-wing lift interference parameter, and (e) tandem-wing lift-to-drag-ratio interference parameter

IV. Vehicle Conceptual Design

This paper discusses some conceptual design work with some proof-of-concept vehicle development efforts. The results of both parallel efforts are summarized and the implications of the accomplishments to date will be discussed in the context of progress towards the ultimate realization of autonomous vertical lift aerial vehicles for disaster relief and emergency response.

There is an ever-increasing number of novel UAVs configurations currently being proposed for a variety of missions, including DRER missions. The primary reasons for the particular vehicle configurations being examined in this paper are that these configurations simultaneous attempt to deal with several key design challenges: improve vehicle cruise efficiency while not sacrificing hover/VTOL efficiency/capability or the simplicity of vehicle trim via flight control by means rotor RPM speed control; consider from the very beginning of vehicle design the safety implications of the vehicle as to potential hazards to bystanders or stationary objects on the ground in the low-altitude flight paths of the vehicle (the primary concern not being the vehicle robustness but its potential for harm to people and property); finally, maximizing the speed and payload capability of intentionally small, low-cost vehicles. The proposed vehicle configurations fall within a spectrum of vehicle concepts spanning from historical fan-in-wing and fan-in-fuselage VTOL aircraft concepts (e.g. Refs. 32-33) to compound/hybrid rotorcraft. Nesting both propellers/propulsors and multiple lifting-rotors between effectively tandem- or joined-wing geometries conceptually addresses all three design challenges. These RED and BLUE SPRITES configurations are also part of the greater sub-class of heterogeneous multirotor vehicle configurations summarized in Ref. 12.

A. RED (Rapid Emergency Deployment) SPRITES

RED SPRITES are one of two general categories of small VTOL UAVs considered in this paper as to DRER missions. RED SPRITES are specifically tailored from a conceptual design perspective to meet the requirements of SAR missions, refer to Fig. 17.

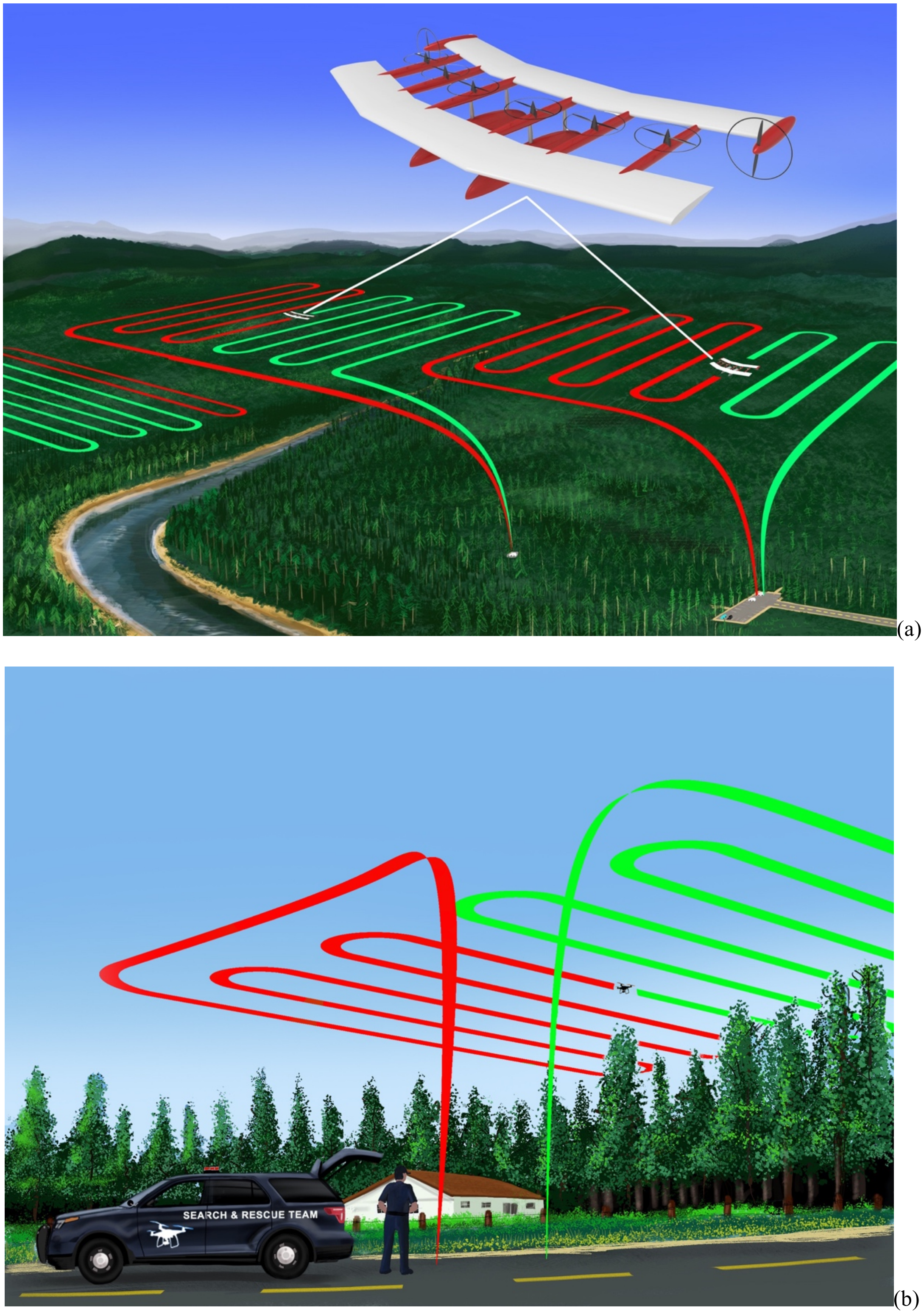


Figure 17. Notional RED SPRITES performing search and rescue aerial surveys over a rural area

Figure 18 illustrates one notional vehicle configuration for a SAR mission (as modeled as a simple configuration in CFD). This concept was first discussed in Ref. 12 in a general sense with respect to key parameters related to cruise aeroperformance for heterogeneous multirotor configurations with spanwise arrays of lifting rotors.

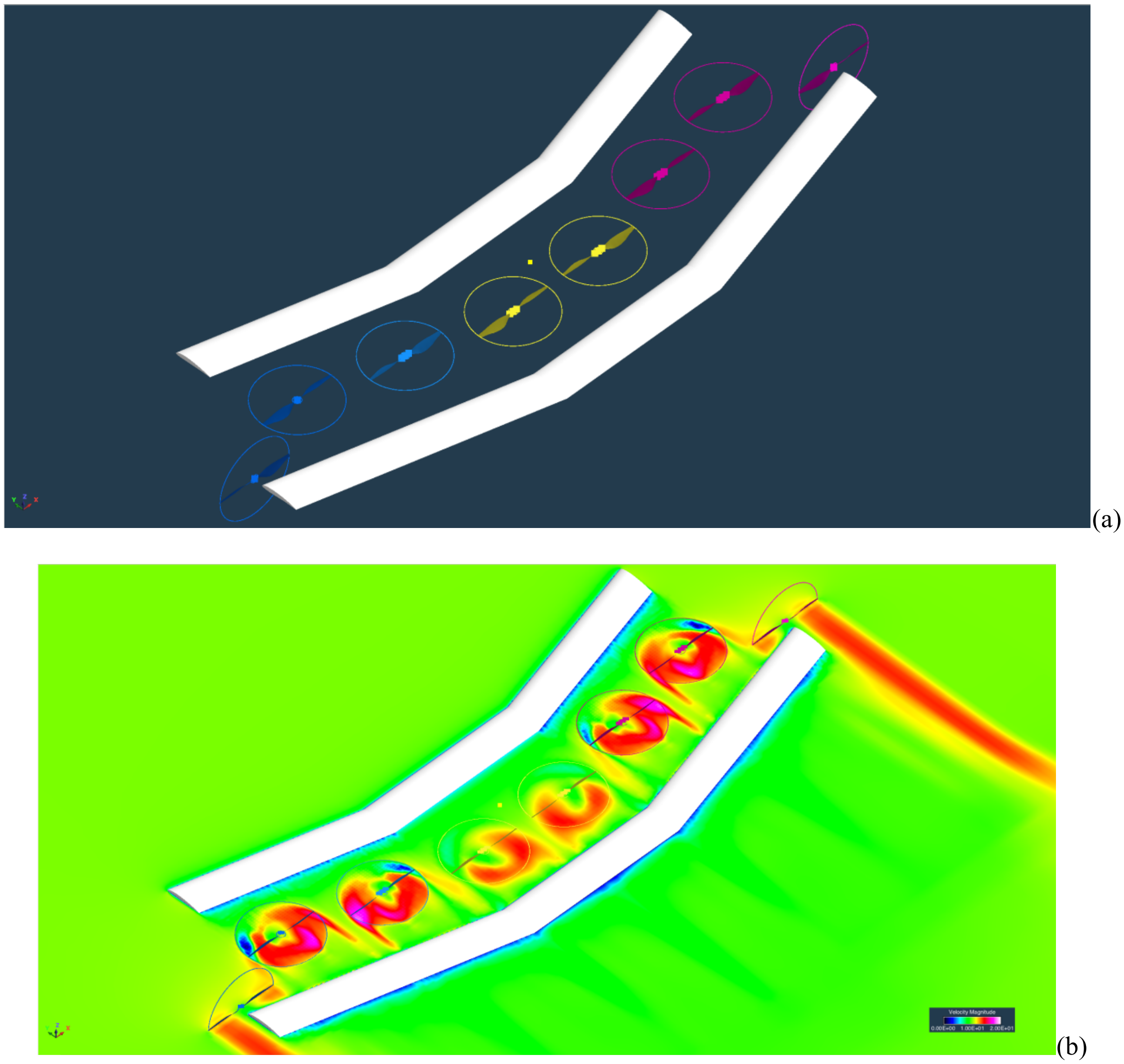


Figure 18. Notional RED SPRITE vehicle configuration modeling in CFD

Operationally, the RED SPRITES vehicle would vertically takeoff and land primarily by the use of its fixed-pitch lifting propellers. Vehicle low-speed attitude-holding and gust rejection would be accomplished in a similar manner as conventional quadcopters and multirotor vehicles by rpm/speed control of a minimum of four of the lifting rotors. The primary justification for the swept tandem wings is not aeroperformance driven but instead is dictated so as to provide longitudinal spacing between pairs of lifting rotors so as to still enable low-speed control of the vehicle via rpm/speed control of the fixed-pitch lifting rotors/propellers. Main forward-flight propulsion would come from the horizontal-axis "propulsor" propellers; throughout the forward-flight regime the vehicle would be kept at a nominal level attitude, unlike conventional quadcopters, etc., where a nose-down is assumed to vector the propellers' thrust forward for forward-flight. At higher forward-flight velocities, the lifting rotors would be spun slower and contribute decreasingly to the overall vehicle lift as the tandem wing geometry begins to carry more of the lift. Yaw control would be performed by differential thrust between the two propulsor propellers. Spun at different rpms/speeds. Current design work continues to focus on the exclusive use of fixed-pitch propellers for lifting rotors and propulsors, however aerodynamic predictions from Ref. 12 would suggest to maximize the overall vehicle aeroperformance efficiency, lifting rotors incorporating rotor collective and cyclic might be required to effect more uniform lateral spanwise loading across the rotors' disks and therein result in an improved aggregate rotor/wing loading and efficiency. Because the vehicle doesn't have to carry a deployable payload a conventional fuselage shape is not required; instead, a streamlined pair of pylons serve dual-purpose as landing gear and stowage of the avionics, sensors, and electrical propulsion components.

B. BLUE (Broad-spectrum Lifesaving through Utility Equipage) SPRITES

BLUE SPRITES utility missions are focused on the notion of a distributed network of vehicles and ground infrastructure that allows for the delivery of high-value air packages in the event of large-scale metropolitan or regional disasters; refer to Fig. 19. The concept is built on the precept that, even in the largest disaster, each call for help is a person, family, neighborhood in need requiring a dedicated/tailored effort to bring relief and aid.

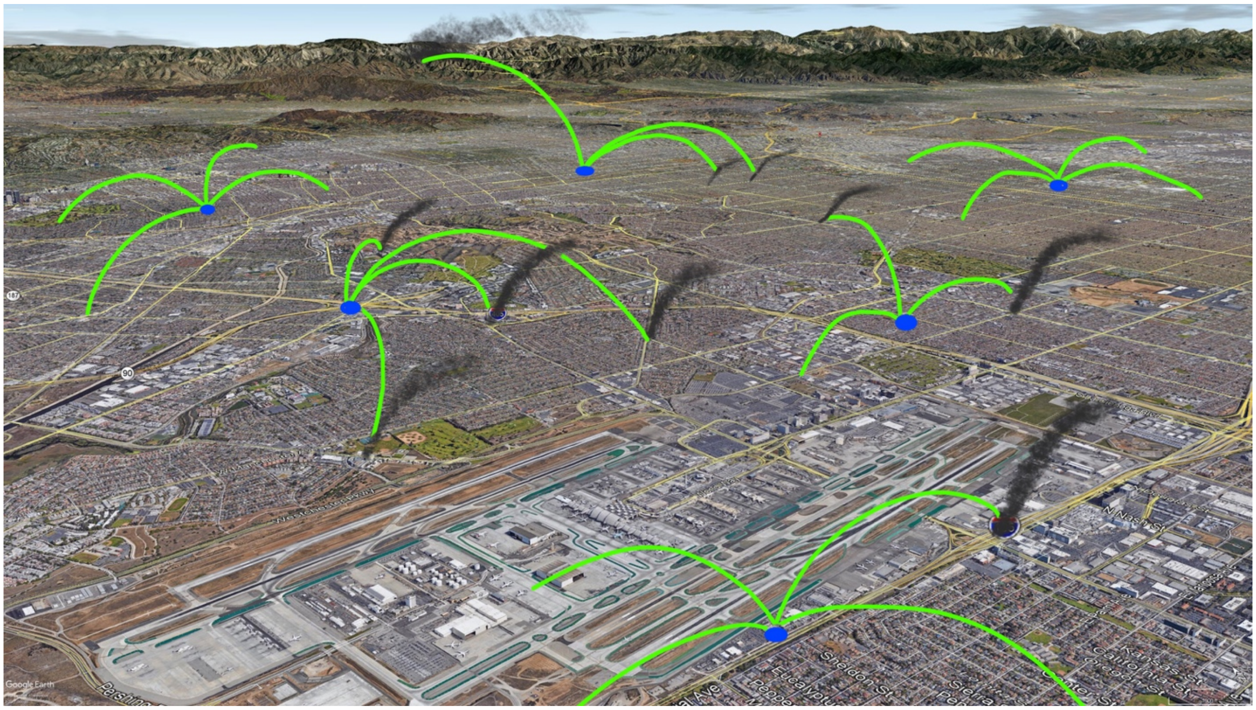


Figure 19. Notional BLUE SPRITES performing small aid package delivery utility missions in an urban environment

Many of the same design and flight control considerations outlined for the notional RED SPRITES vehicle discussed previously are also broadly applicable to the BLUE vehicles: use of tandem wings to "nest" the lifting rotors (therefore inherently embodying a "design for safety" approach to protecting people and objects from the rotors); lateral spacing of lifting rotors to successfully effect rpm/speed control of fixed-pitch propellers for vehicle attitude control; wings and propulsor-propellers for efficient forward-flight cruise. But, additionally, the particular configuration currently being studied has hints of bio-inspiration (insect- or, specifically, butterfly-like) with respect to its overall rotor/wing geometry while, at the same time, incorporating a more conventional fuselage shape to accommodate deployable packages/payloads as required by the BLUE SPRITES utility mission.

V. Test Model Development

As a part of this initial SPRITES research effort, some initial test model development has been pursued. The test models were primarily developed to elicit an improved understanding of some of the design and fabrication challenges of RED- and BLUE-type SPRITES vehicles, i.e. vehicles devoted respectively to SAR and disaster relief utility (wherein small, critical packages or equipment might be deployed) missions.

To cost effectively perform this test model development, a heavy reliance on additive manufacturing and COTS components was required. Small test specimens and components were first designed, fabricated, and assembled to test articles to test various model construction approaches. Larger components were then fabricated and assembled into near-full-scale test models. The result from a weight perspective was heavier than desired as flight articles but acceptable as have and tie-down test models.

The test models are based significantly on the design concepts outlined in Ref. 12. Two test model development efforts are being conducted in parallel – i.e. test models of both RED and BLUE SPRITES are being constructed; refer to Figs. 20-22.

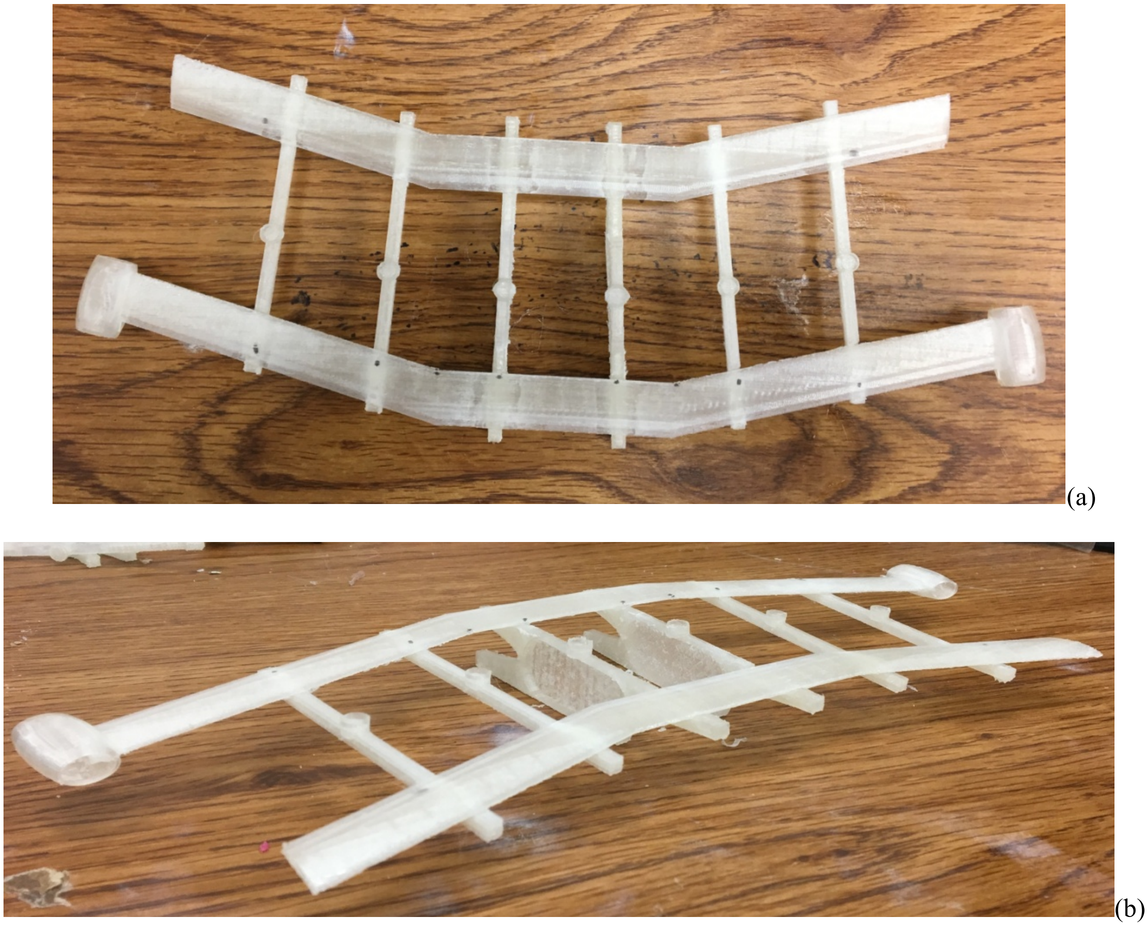


Figure 20. RED SPRITES small-scale 'frame' prototype: (a) planform and (b) orthogonal views

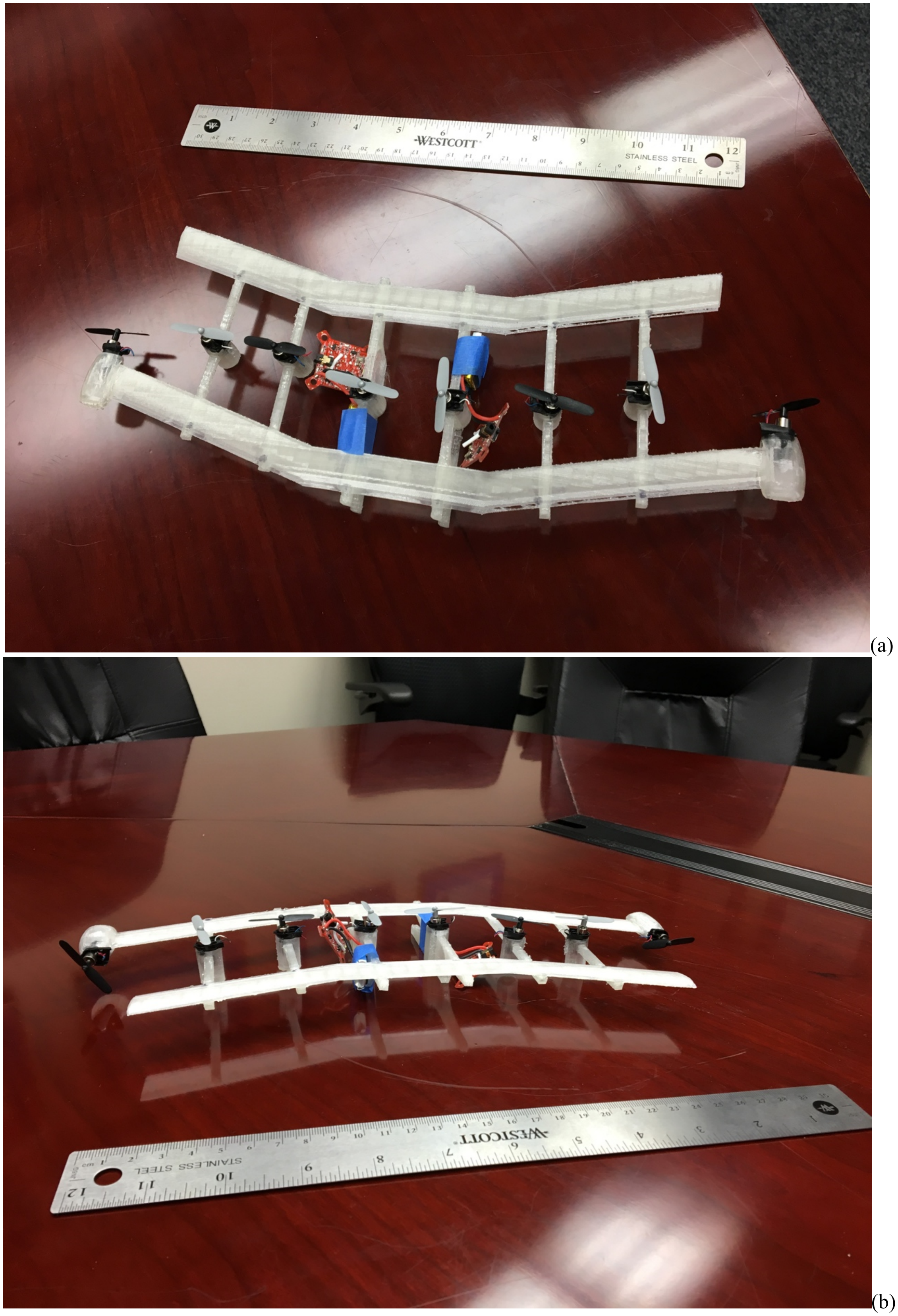


Figure 21.   RED SPRITES with rotor/propeller mock-up: (a) planform and (b) orthogonal views

Additionally, work is also in progress on developing a BLUE SPRITES test model. A generic fuselage has been developed based on using NACA 0012 airfoil coordinates to generate a body-of-revolution. This generic fuselage is intended to be used for a number of UAV/VTOL aircraft test model development efforts at NASA Ames Research Center. Figure 22a-b are photographs of the test model in early stages of development. With the in-parallel RED SPRITES model development effort, additive manufacturing using PLA filament is being used for the component fabrication. Later development efforts will use more structurally robust and low-weight construction techniques.

Figure 22. BLUE SPRITES large-scale test model fabrication in-progress

An alternate vehicle implementation of a BLUE SPRITES vehicle would be the multi-modality VTOL vehicle platform discussed in Ref. 16; refer to Fig. 23. In fact, any so-called "delivery drone" could be considered a vehicle candidate for BLUE SPRITES utility-type missions. The natural mission profile alignment between delivery drones and BLUE SPRITES suggests that some sort of on-extreme-demand, dual-use deployment of commercial delivery drones to support DRER missions might be a good approach towards developing/implementing economically feasible large SPRITES networks for large-scale (but hopefully rare) emergency response and disaster relief efforts.

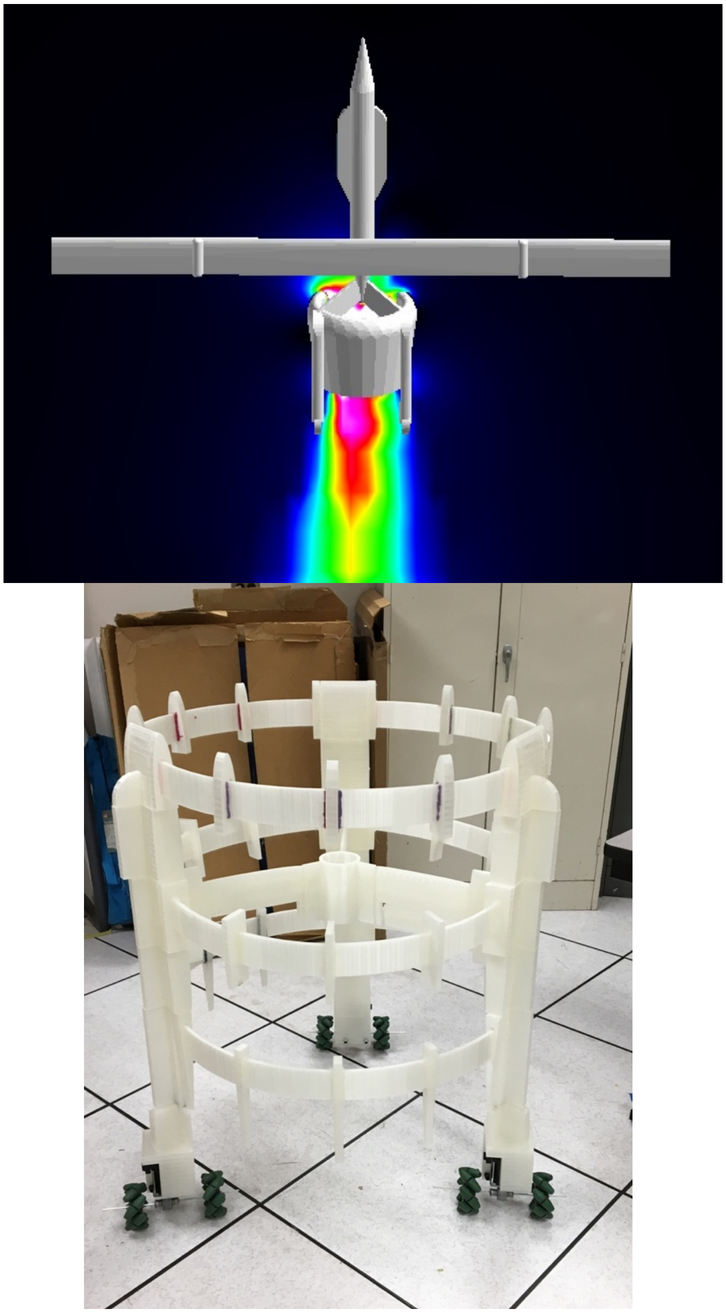


Figure 23. BLUE SPRITES synergy with respect to "delivery drones," specifically in this case to the MICHAEL project (Ref. 16): (a) CFD hover prediction and (b) in-progress prototype test model fabrication

VI. Concluding Remarks

Another year and, unfortunately, another major disaster it seems. As this paper was being written, Hurricane Harvey flooded Houston and surrounding cities and towns, Hurricane Irma severely impacted Florida, Hurricane Maria devastated Puerto Rico, and a 7.1 earthquake killed hundreds of people in central Mexico. All this during the course of a couple of months. Such disasters have become a too common event in both the United States and around the world. It is a key proposition of this paper that vertical lift, uninhabited aerial vehicle, electric propulsion, intelligence system and robotics technologies have all matured to the point that great strides can be made to improve world-wide capabilities with respect to disaster relief and emergency response missions. The proposed uninhabited aerial vehicles can only be a small part of the overall response to large-scale disasters but in those critical moments of an emergency where time and access are crucial for saving lives, such vehicles might be a powerful tool. This is the latest in a continuing series of papers examining the potential impact of autonomous vertical lift aerial vehicles for disaster relief and emergency response missions.

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