A Future for Rotorcraft that Engages with New Application Domains

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ABSTRACT

The objective of this paper is to present ideas related to possible new application domains to consider for future rotorcraft research and development efforts. Some of these application domains have been points of discussion in an earlier body of work at NASA Ames Research Center, but some are anticipated to be wholly new. The goal is to aid in securing a robust and expansive rotorcraft research community for the next four decades at least. To achieve that goal and to pursue the identified new application domains, it will be essential to engage in collaborative networking with other research communities such as intelligent systems developers and roboticists.

NOMENCLATURE

A	Rotor disk area, ft^2; $A=\pi R^2$
CATS	Climate-adjusted air transportation systems
C_P	Rotor, or proprotor, or fan power coefficient, nondim.; $C_P = P/\rho A V_{tip}^3$
C_T	Rotor, or proprotor, or fan thrust coefficient, nondim.; $C_T = T/\rho A V_{tip}^2$
DRER	Disaster relief and emergency response
DOF	Degree-of-freedom, nondim.
L/D	Lift to drag ratio, nondim.
L/D_e	Effective lift to drag ratio for rotorcraft, $L/D_e = WV/P$
P	Vehicle total power,
PAV	Planetary aerial vehicles
PAX	Number of passengers, nondim.
R	Rotor radius, ft
RAR	Rotorcraft as robots
RIA	Runway independent aircraft
SAS	System analysis as applied to autonomy
SMR	Single main rotor
S	(Fixed-) wing planform area, ft^2
UFM	Universal flying machines
V	Cruise velocity, ft/s (m/s
W	Takeoff gross weight of vehicle, lb_f
α	Angle of attack, Deg.
β	Sideslip angle, Deg.
Γ	Wing dihedral/anhedral angle, Deg.
$\Delta D_e/L$	Delta effective drag to lift ratio, nondim.

INTRODUCTION

This paper describes a possible future for rotorcraft and the rotorcraft research community that would emphasize new mission application domains that respond to emerging, or largely unaddressed by aviation, societal problems. This paper emphasizes

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[1] Presented at the 11th Biennial Autonomous VTOL Technical Meeting, Phoenix, AZ, Feb 4-6, 2025. Work of the US Government and not subject to Copyright protection.

that vehicle autonomy is an integral aviation capability necessary for the future.

The overarching objectives of the paper are to:

(1) present a perspective of engineering innovation for early career engineers,

(2) plant the seeds for possible research and innovation within the rotorcraft research community for the next two or three decades, and

(3) inspire cross-disciplinary and community collaboration.

Societal problems should drive new fields of study and new application domains. Not all societal problems have technological solutions. Not all technology solutions have an aerospace/rotorcraft component to them. However, there are far more societal problems that could be at least partially addressed by rotorcraft and rotary-wing technologies than have been imagined to date, and this paper addresses this gap.

BACKGROUND

Examples of some societal problems that could be partially addressed by rotorcraft/aviation are: disaster relief and emergency response (i.e., responding within the 'golden hour' no matter where, or how far, or under what circumstances); terrestrial and planetary science (i.e., science everywhere, all the time, for everyone); wildlife conservation/preservation (i.e., to minimize/prevent the sixth mass extinction, aka 'great die-off,' of life on our planet); improving the livability of cities and strengthening rural communities.

The following areas of research will be discussed: (1) Planetary rotorcraft (vertical lift planetary aerial vehicles, Refs. 1-3); (2) 'Rotorcraft as robots,' (aerobots as a ubiquitous part of society, Refs. 4-5); (3) Disaster relief and emergency response using autonomous vertical lift aerial vehicles, Refs. 6-8; (4) 'Resilience in aviation systems,' where this includes urban and regional rotorcraft networks, novel modular and scalable aerial vehicle designs, and accessibility and standard of living considerations in emerging aerospace applications, Refs. 9-10; (5) 'Universal flying machines,' i.e. static and reconfigurable structures composed of flying elements; machines with rotors/thrusters as actuators versus conventional servo-motors and linear-actuators; (6) High-speed rotorcraft to close the productivity gap between rotorcraft and commercial aircraft, Refs. 11-13; (7) Transforming or morphing hybrid multi-modal aerial vehicles including variable geometry vehicles and modular and/or distributed, homogeneous or heterogeneous, vehicles, Refs. 13-14; (8) Smart, multifunctional, variable-geometry (rotating and fixed-frame) structures and/or subsystems, Refs. 15-16; (9) Opportunities for space and aeronautics synergy (in addition to planetary rotorcraft); (10) Advances in emerging areas of system analysis, including 'system analysis as applied to autonomy', sizing analysis of hybrid multi-modal systems, and new societal metrics to factor into design (e.g. livability indices); and (11) Asymmetry in aircraft/rotorcraft design for enhanced functionality and capability.

The common set of themes for these eleven research areas are listed as follows:

- Autonomous system technology
- Robotics and GNC (guidance, navigation, and communication) advances

- All-electric and hybrid-electric propulsion, battery and/or fuel-cell, and power electronics advances.
- Variable geometry and/or modular rotorcraft subsystems or vehicles
- Hybrid air/ground or air/sea mobility

THE NEED FOR NEW APPLICATION DOMAINS

For the rotorcraft research community to grow in the future, it is necessary to think beyond the well-established aviation markets for commercial and military helicopters and tiltrotor aircraft. Even with the recent emergence of the eVTOL urban air mobility (UAM) application, there is still considerably more work needed within the rotorcraft community to consider other application domains. But, even more important than that, there are clearly unaddressed or under-addressed societal problems that could be addressed, in part, by rotary-wing technologies and/or rotorcraft vehicles.

The bulk of the early work cited in this paper is that of the Aeromechanics Office at NASA Ames Research Center. This does not mean, though, that other researchers in the past have not touched upon or worked in similar nascent application domains. What is perhaps most pressing now versus back then, at the time of the earlier work, is that many of the societal problems noted back then have only unfortunately worsened with time.

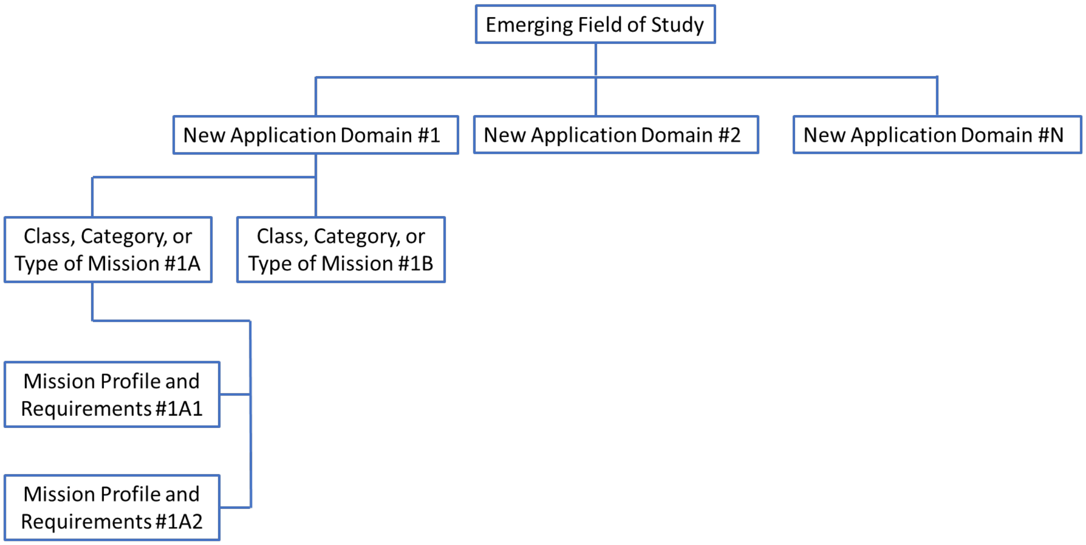


Figure 1. Generic Flow Chart of Emerging Fields of Study vs. New Application Domains vs. New Types of Missions

Note that there is some inevitable confusion between an ‘emerging field of study’ versus a ‘new application domain.’ In a few cases in this paper, a ‘new application domain’ is listed/summarized in the text but, admittedly, what is being summarized is more one of an ‘emerging field of study’ (to which, as shown in Fig. 1, there can be many application domains that can fall under a given field of study). The distinction between the two will hopefully be made clearer as one proceeds through the paper.

As a body of work builds up with time, there begins to be developed a certain level of formalism in the treatment of that area of research. With increasing formalism, it consequently becomes more efficient to generate new ideas and technical approaches in the emerging field of study and its associated application domains.

The fields of study – and associated new application domains suggested – are not intended to be comprehensive. Instead, this paper should be a considered a call to action to consider the future of the rotorcraft research and development community.

RECOMMENDED NEW APPLICATION DOMAINS

The following discussion summarizes the recommended new fields of study and new rotorcraft application domains.

Vertical lift planetary aerial vehicles

NASA Ames has held for twenty-five-plus years a leadership role in planetary rotorcraft, e.g., Refs. 1-3. Ingenuity and Titan Dragonfly are just the beginning though. New types of planetary aerial vehicles should be developed. For example, the planet Venus might be the next planetary rotorcraft opportunity. Or, alternatively, planetary aerial vehicles for the outer giant planets might be worth exploring (for likely non-rotorcraft aerial vehicles). And consider this, a propeller is effectively a rotor: Mars/Venus airplanes could be investigated by the rotorcraft community (and not just by the fixed wing airplane community). Synergy with, and expansion of, terrestrial field science campaigns could be an outgrowth of planetary rotorcraft work.

Figure 2 presents an illustrative example of a flow chart for the planetary aerial vehicle field of study (with emphasis, because of the necessity for brevity, on Mars).

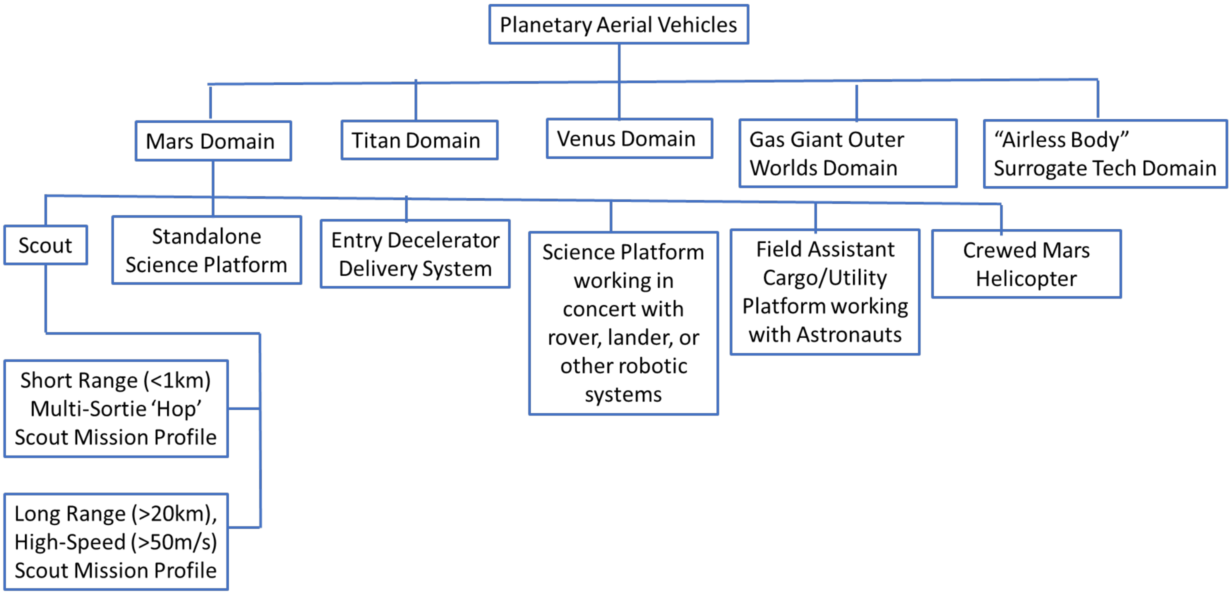


Figure 2. Representative Example of a Flow Chart for Planetary Aerial Vehicles Field of Study, Application Domains, and Types of Missions

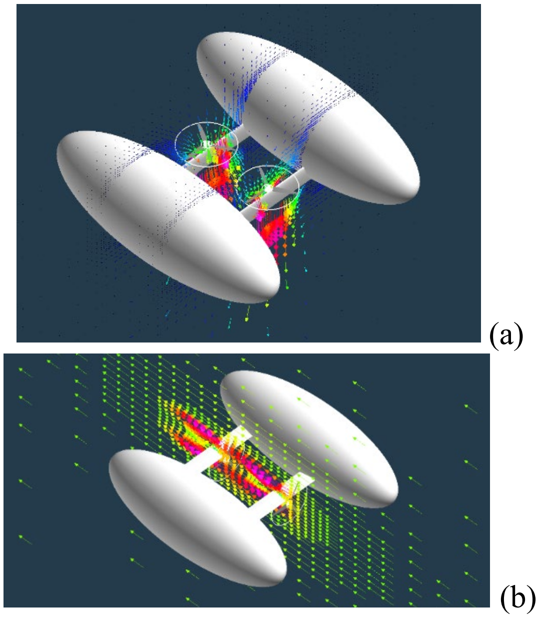


Figure 3. Venus flyers (hybrid rotorcraft for near-surface flight, Ref. 17), (a) hover and (b) forward flight

Flight on Venus, near its surface will be very difficult because of the tremendous pressures and high temperatures near the surface. But the problem of flight becomes more tractable the higher the altitudes to be flown at during a planetary mission. Despite the major environmental challenges it poses, rotary-wing flight near the surface should not be abandoned though. Figure 3 is one notional vehicle configuration (twin hulls internally pressurized with tandem tilting wings and propellers in this example) for such near-surface flight, see Ref. 17. The high temperatures near the surface might limit mission duration near the surface to a few hours, because of the onboard electronics heat death, but undertaking and delivering such a Venus flyer mission would be a major planetary science accomplishment.

An alternate type of Venus mission is the use of rotary-wing decelerators for descent into the atmosphere of Venus (Fig. 4). This is perhaps less challenging than the VTOL flyer because most of the descent will be at altitudes where the density, pressure, and temperatures are less severe than at the surface and 'heat death' of the onboard electronics can be delayed.

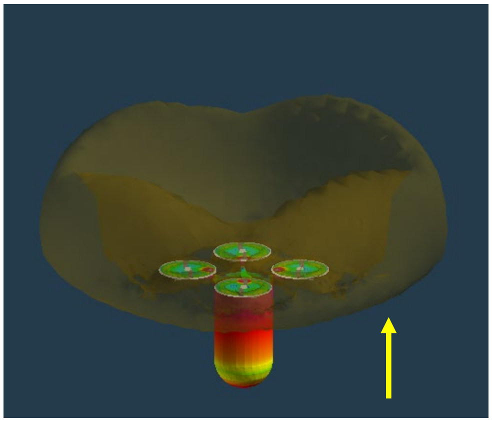


Figure 4. Notional Venus Descent Rotary-Wing Decelerator (Ref. 18)

Rotorcraft as robots

The emerging field of 'rotorcraft as robots' (RAR) provides the aspirational goal to think beyond just autonomous helicopters (i.e., doing more than merely replacing the pilot). Rotorcraft that are surface- and object-interactive and multi-modal; and rotorcraft that have effector/actuator capabilities, see Fig. 5. Additionally, this includes robotic rotorcraft that interact with other robotic systems for complete missions and even complete vehicle life cycles. 'Rotorcraft as robots' could have a profound influence on how future terrestrial field science, environmental, and biodiversity monitoring will be conducted in the future.

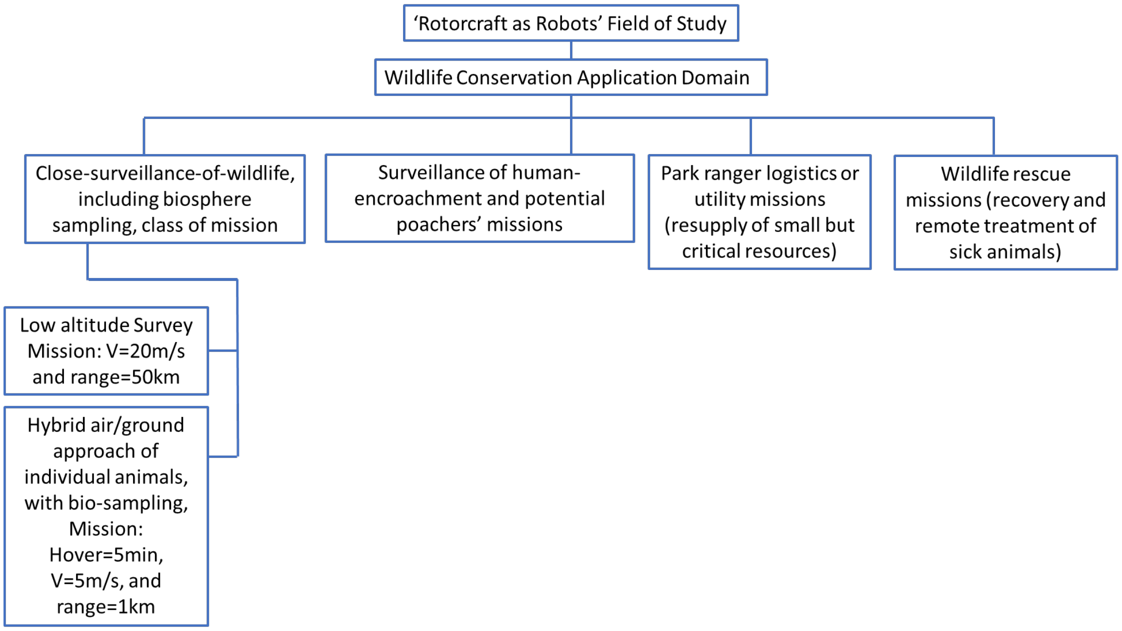


Figure 5. 'Rotorcraft as robots' supporting wildlife conservation (one example of a multitude of RAR applications)

Figure 6 is a notional artwork of RAR assets used for wildlife conservation.

Figure 6. RAR potential serving wildlife conservation missions; AI-generated artwork from Microsoft Copilot software

Figure 7 is one potential RAR hybrid air/ground mobility robotic system. In this case, the ground mobility is provided by passive legged locomotion (motive force provided by propellers) with propellers that are tiltable to switch between one mode (propeller rotational axes are horizontal) where the propellers aid ground mobility and switch to another mode where the propellers are tilted vertically and support air mobility.

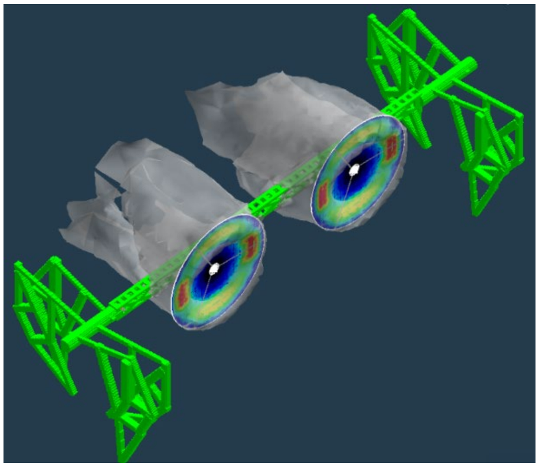


Figure 7. CAD/CFD model of robot with tiltable side-by-side rotors integrated with Jansen walking machine

‘Rotorcraft as Robots,’ though perhaps not generally well known by that title, is perhaps one of the most widely developed of the new fields of study noted in this paper. Electrical engineers, computer scientists and technologists, and roboticists have significantly embraced the use of readily available commercial off the shelf (COTS) microelectronics, micromechanical control actuators, and multirotor drones or UAVs to investigate novel aerial robotic systems, e.g., Refs. 4 and 19. Early work at NASA Ames Research Center helped pioneer some of these investigations but this type of research saw most of its subsequent advances from nontraditional (with respect to rotorcraft) research communities. Despite some noteworthy work by academic researchers, e.g., Refs. 32-33, this application domain is largely unexplored by the rotorcraft community. The ‘rotorcraft as robots’ field could benefit from rotorcraft expertise in defining practical mission CONOPS and fieldable systems.

Disaster relief and emergency response using autonomous vertical lift aerial vehicles

Ever since the first practical helicopter, helicopter use for search and rescue has been the rotorcraft community’s first and most important application domain.

Disaster relief and emergency response (DRER) is the first and best use of helicopters, but the same will be true for autonomous vertical lift aerial vehicles. Such vehicles can potentially span two or more orders of magnitude of gross weight, payload, range/endurance, and speed. Such DRER aerial vehicles will be used to monitor, warn, aid, rescue, and rebuild (MWARR). Cross-mission and application synergies (between defense, commercial delivery, and DRER) are possible, and likely necessary, to arrive at large, cost-effective, and highly responsive networks.

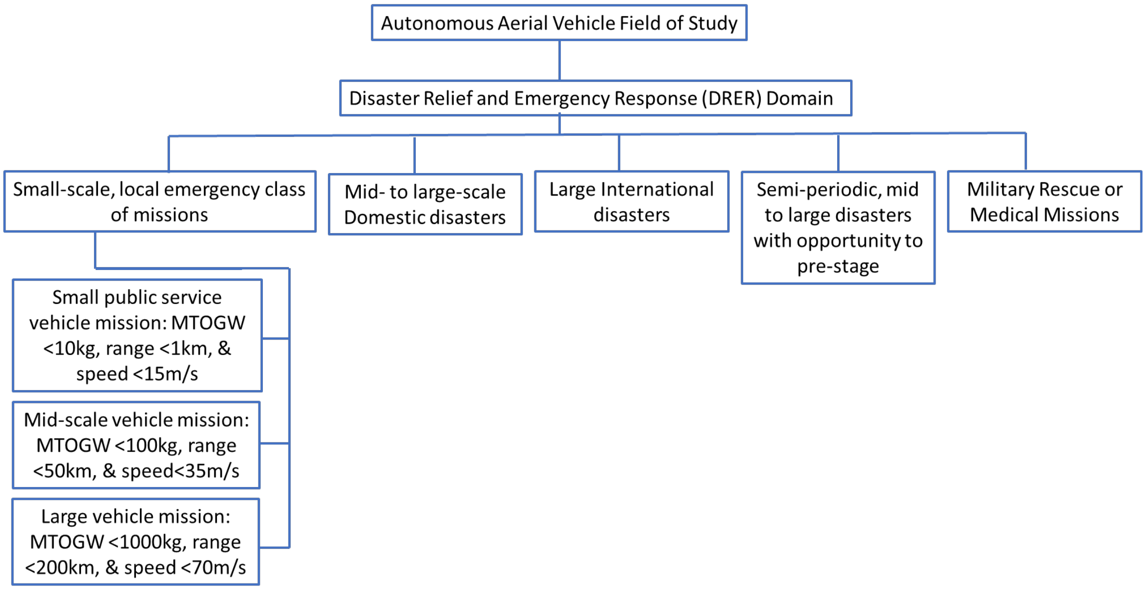


Figure 8. Autonomous aerial vehicles and disaster relief and emergency response applications and missions

There has been research at NASA Ames Research Center into autonomous aerial vehicles – and how they could support DRER missions – since the 2000 timeframe, e.g., Ref. 20. In recent years, there has been increased interest in DRER missions for rotary-wing UAVs, e.g., Ref. 21.

Figure 8 summarizes some potential DRER application domains and sample classes of missions. A large spectrum of vehicle sizes, mission capabilities, and new technologies are possible for DRER. Currently, the NASA technology portfolio for DRER is focused on wildfire response and more on UAV traffic management (UTM) considerations and not so much on vehicle-centric research and development activity, e.g., Ref. 29. Hopefully, this will change in the future; there are substantial opportunities to consider novel vehicle designs for DRER missions, see, for example, Fig 9a-b.

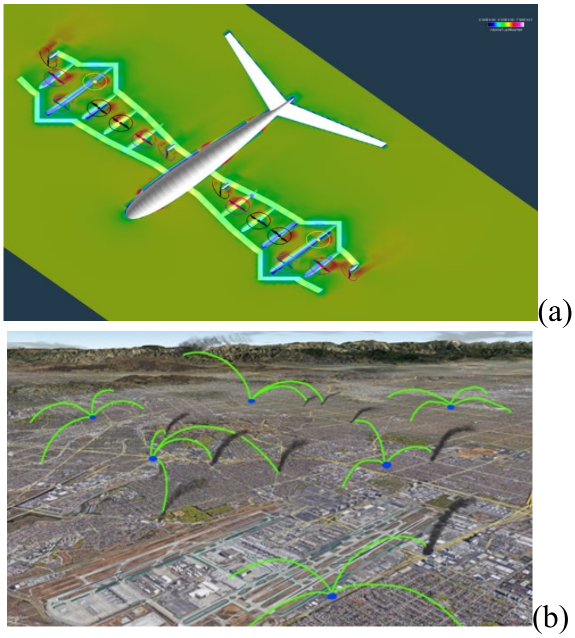


Figure 9. DRER: (a) damage surveys and (b) urban emergency aid networks

The introduction of rotary-wing UAVs, or drones, to support DRER and other public service missions will likely be enhanced by using these aerial assets in a dual-purpose (commercial and public service vehicles), coordinated manner.

Resilience in aviation systems

The aviation sector is a very complex but generally successful enterprise within the United States. It spans a spectrum of stakeholders that ranges from: the traveling public, to aircraft researchers and developers, to airport operators, to airlines and other aircraft operators, to the public/government regulators and officials. Overall, the aviation sector is critical to the smooth operation of society. After a series of demonstrable major disruptions to aviation over multiple decades, it is appropriate to consider how to enhance the overall resilience of the aviation sector. This will entail developing research programs that promote system-of-systems engineering solutions that focus on vehicle design advances and novel airspace system architectures.

To accomplish this goal, it is necessary to consider engineering solutions to make the aviation sector more resilient to anticipated and potential future crises.

1. How can the aviation fleet be quickly ‘right sized’ and/or re-configured to meet the challenges of rapid changes in the economic operational environment?
2. How can aviation be refined to improve economic opportunities for urban and rural/regional communities in the US?
3. How can aviation respond to changes stemming from environmental challenges, including climate change?

4. How can aviation evolve to respond to the ever-increasing challenges of disaster relief and emergency response?

The following are some foundational principles that can aid in addressing the above questions:

I. Vertical lift and short takeoff and landing (STOL) aerial vehicles, particularly those having hybrid-electric propulsion, have the potential to expand into and fill several subsectors of the aviation sector.
II. Autonomous systems and robotics technology also potentially have a profound influence on aviation.
III. Aviation can and must expand to new markets and to new applications to meet critical societal needs. This, in turn, will economically sustain aviation during difficult times.
IV. Modular and distributed vehicles and/or subsystems could radically change aircraft design and operations.
V. Wholly new types of amphibious and multimodal vehicles and networks also have an opportunity to transform urban and regional aviation markets.
VI. A broad spectrum of vehicle sizes and capabilities will be required for building aviation resilience (e.g., disaster relief and emergency response, Refs. 5-20.

Figures 10-11 are some examples of how runway independent aircraft (VTOL, VSTOL, and STOL aircraft) will be a vital component of enhanced aviation resilience.

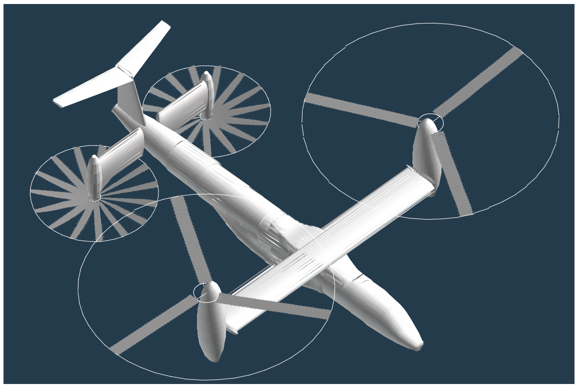


Figure 10. Runway independent aircraft (RIA) for aviation resiliency (Ref. 11-13 and 22-23)

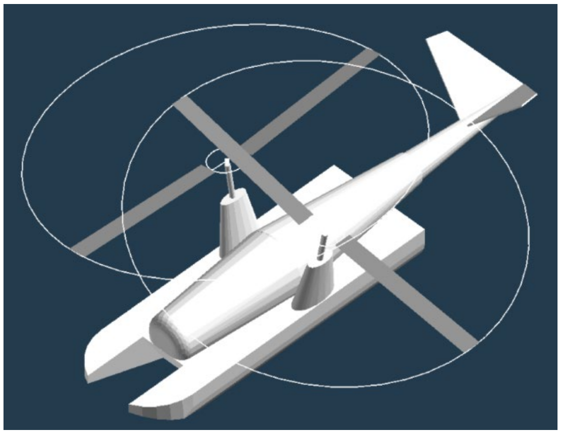


Figure 11. An emerging possible role for amphibious rotorcraft/aircraft (Ref. 24)

Figure 12 illustrates a possible new generation of STOL or V/STOL aircraft to maximize mission flexibility by being able to operate from vertiports, short or long runway airports, and even operate amphibiously. It emphasizes the use of distributed and heterogenous rotors and, further, tilts the wings and rotor nacelles independently to enable this V/STOL flexibility.

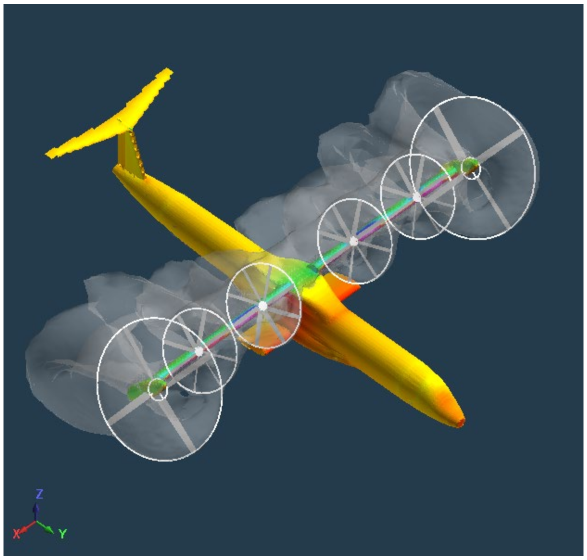
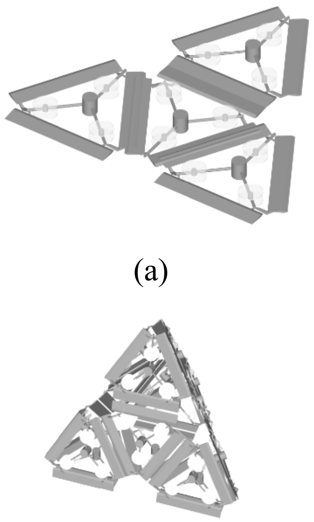


Figure 12. Hybrid tiltwing/tiltrotor aircraft with heterogeneous rotors and propellers (Ref. 23)

Universal flying machines

Universal flying machines (UFM) are conceived of as modular rotorcraft ‘elements’ physically joined to form temporary reconfigurable structures and/or on-demand ‘constructs’ (i.e., modular machines or vehicles). This work lies at the intersection between ‘swarms’ and modular systems. In that regard, UFM can be considered large-scale flying Lego^{TM} bricks or Tinkertoy sets. Equally important, though, UFM could also be used to build simple or modest machines that make use of rotors/thrusters as motive-force ‘actuators’ in ‘constructs’ versus motors and linear actuators.

A considerable body of work exists with regards to swarms of robots, aerial or otherwise. However, less work has been focused on the notion of multiple robots structurally intertwined/semi-integrated (if only for a short time with or without limited aggregate, or ensemble, versus individual robotic subsystem functionality/actuation). The term “construct” is introduced in this paper as a general term to be applied to all these collective intertwined/semi-integrated multi-robot assemblies. Also, for the purposes of this paper the individual robotic systems will be referred to as “elements.” When aerial mobility is an important attribute of either the elements or the construct, or both, then also for the purposes of the paper, the elements and constructs are interchangeably referred to as universal flying machines (UFM), see Fig. 13. Nothing in this terminology precludes swarms of robots forming and decomposing from swarms to constructs back and forth upon need. Nothing in this notion of construct prohibits the intertwined/semi-integrated multiple robots be passive or stationary during integration, nor does it exclude the possibility that the integrated construct has unique aggregate/ensemble mobility, enhanced, or transformed, actuation or manipulation capabilities, or other types of collective versus individual element robotic functionality. Ideally this formation and/or decomposition of constructs from elements should happen without external assistance either manually from people or from independent robotic assembly systems. This ideal, though, is not an absolute requirement and there are many applications/missions where this requirement is unnecessary. Additionally, it is also acceptable to consider constructs whose formation or decomposition is a one-way or nonreversible process. An inherent, intrinsic requirement of the construct, and consequently the universal flying machine, concept is the need for transitory formation and decomposition of constructs from elements.


(a)

(b)

Figure 13. UFM elements that could reconfigure to form structures, aggregate assemblies or constructs, and even simple machines

High-speed (and high-productivity) rotorcraft

The NASA Aeronautics Research Mission Directorate's RVLT project has substantially invested over the past five plus years on research into the development of urban air mobility (UAM), aka eVTOL, vehicles. This parallels a very large development effort by an emerging eVTOL industry, see Ref. 25. Such eVTOL vehicles are on track to be certified by the FAA in the next couple of years and then become commercially available. This then begs the question of 'what next?' for rotorcraft research, see Fig. 14. The one possible answer is to revisit past interest into rotorcraft that can support regional commercial markets, and, further, (re)emphasize higher speed flight, while at the same time emphasizing the need to incorporate into these regional high-speed rotorcraft sustainable aviation attributes. High-speed (>275 knots cruise), regional (range>500 nautical miles (nm)) rotorcraft will build in needed reliance in the aviation system of the future; providing sustainable aviation capability, in parallel, is also a worthwhile cause.

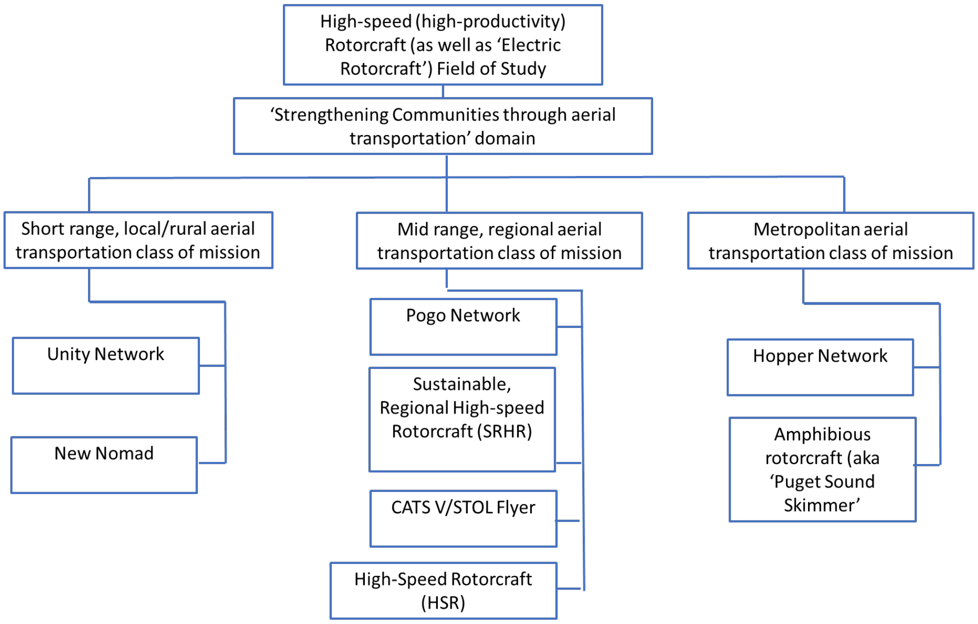


Figure 14. High-speed (and/or high productivity) rotorcraft

One possibility to investigate is the sustainable, regional, high-speed rotorcraft (SRHR) concept that seeks to address the following problem: how to best arrive at a class of rotorcraft that has higher speed, has regional-scale range capability, retains VTOL capabilities, but also embodies technologies and vehicle/system designs that emphasize sustainable aviation goals. The overall problem can be broken down into two parts: why do regional high-speed rotorcraft need to be developed and, secondly, if needed, why, and how much, should they embody sustainable aviation capabilities? The NASA rotorcraft community in the past has devoted a considerable amount of research into the potential benefits of regional rotorcraft supporting the commercial passenger transport role; this includes the Short Haul Civil Tiltrotor (SHCT) and the Runway Independent Aircraft efforts of the early 2000's. NASA also in the past has a large body of work considering the technical feasibility of high-speed rotorcraft, with the primary focus of that effort on tiltrotor aircraft. This past work on civil tiltrotor, high-speed rotorcraft, and 'runway independent aircraft' would suggest focusing on high passenger counts and speed to make a regional rotorcraft more economically competitive against regional jets and turboprop aircraft. After the definition of the overall problem, the next step is to define the overall proposed effort objective to identify those technologies and conceptual designs that make a modest but significant impact on reducing the carbon footprint of this proposed new class of SRHR; more specifically, the objective is to have an SRHR hybrid-electric vehicle provide 10-20% of the total mission energy expended to come from electrical power. Preliminary work, Ref. 11, has studied novel SRHR vehicle concepts that targeted twenty-five percent of VTOL and hover power to be derived by electric propulsion running in parallel with turboshaft engine mechanical power supplied to the rotors; cruise power was provided solely by the turboshaft engine in this early study; the net effect of this design trade study sizing analysis was energy provided by electric propulsion to be about 5-10% of the total mission energy. (Only limited effort is currently being expended within NASA as to applying sustainable aviation goals to regional, high-speed rotorcraft.)

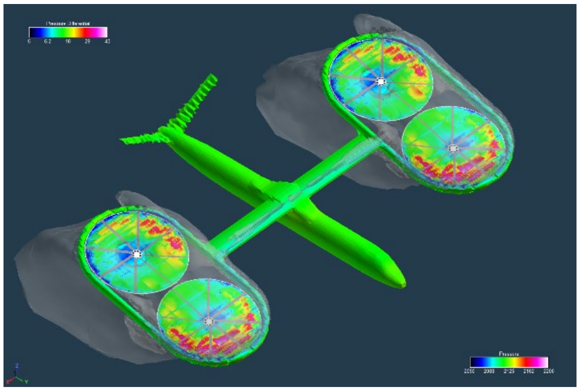


Figure 15. Tilting ducted-fan sustainable regional high-speed rotorcraft concept (Refs. 11-12); low-speed helicopter-mode

Three different hybrid-electric propulsion concepts should be studied in the future: (1) battery (and/or hydrogen-based fuel-cells) and electric motors partially offsetting turboshaft mechanical power to the rotors during vertical takeoff and landing and hover (with turboshaft power only during cruise); (2) turboshaft-driven dual-use electric motor and generator for discharging/charging battery storage inflight for on-demand rotor power augmentation; (3) turboshaft-driven generators providing full flight power to electric motors, which are the sole means of delivering rotor power. New or refined analysis tools as well as new technologies and propulsion architectures will need to be explored. Some preliminary work by industry is looking to extend their UAM/eVTOL vehicles to regional markets but these vehicles are comparatively small (4-6PAX) and do not represent the size of vehicle necessary for regional commercial passenger transport (>50PAX).

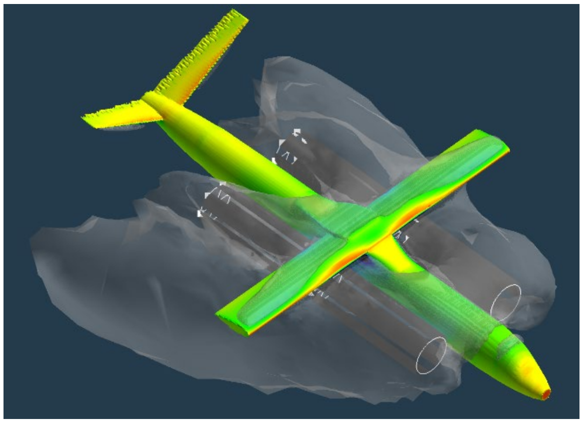


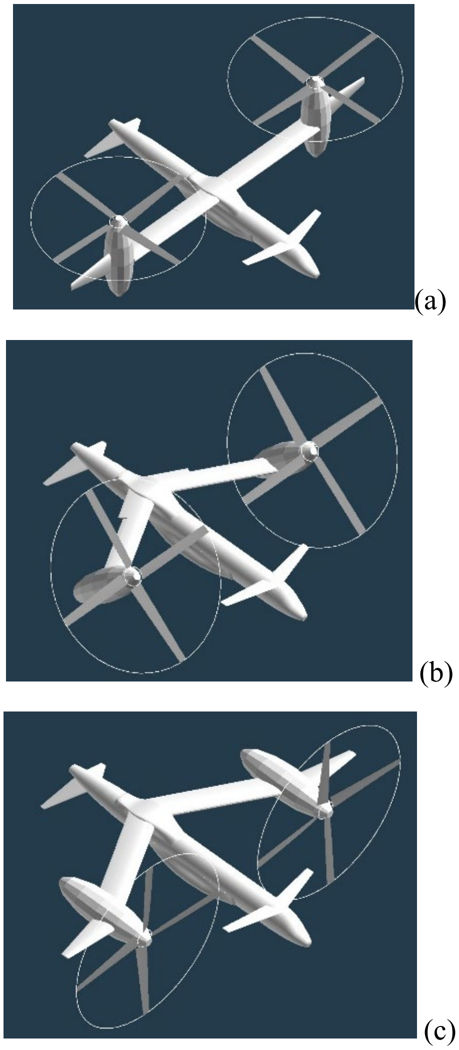
Figure 16. One notional high-speed rotorcraft: stopped cycloidal rotor aerial vehicle (Ref. 11)

Transforming/morphing hybrid multi-modal aerial vehicles

Another field of study for future rotorcraft are 'transformers' (extreme variable geometry, aka 'morphing,' or hybrid multi-modal) rotorcraft; for example, refer to Fig. 17, a notional variable geometry tiltrotor aircraft with variable sweep and longitudinal positioning.

Though there are nontrivial downsides in terms of vehicle weight, there are also significant potential mission capability advantages of variable-geometry morphing rotorcraft as well as hybrid multi-modal vehicles.

Though these types of vehicles have primarily been examined for fixed-wing aircraft, this design space is largely unexplored for rotorcraft. See Ref. 13 for some more advanced tiltrotor aircraft concepts.



(a)

(b)

(c)

Figure 17. Notional variable-geometry tiltrotor aircraft (Ref. 13): (a) hover configuration, (b), transition or conversion and (c) cruise configuration

Smart, multifunctional, variable-geometry structures and/or subsystems

The field of study of smart multifunctional variable-geometry structures (especially variable-geometry rotors) and/or subsystems is at least a forty-year effort within the rotorcraft community. It is suggested that this whole field of study might be rebranded as the 'Babbage[2] program.' Why this field of study has renewed relevance in recent years is twofold. First, continued advances in low-cost COTS microelectronics and micromechanical systems. Second, the potential promise of 'electric rotorcraft' whereby providing for electric-propulsion for aerial vehicles also enables the potential for electrically powering active flow control devices on the airframes and rotors of such aerial vehicles as well as powering variable-geometry devices. Previously, enabling such devices would result in too much delta increases in power, weight, and complexity (and cost) to be implemented onto a production aircraft.

This field of study continues to have a lot of potential and could greatly benefit from having a unifying foundation to build upon. Use of the 'Babbage program' label is one small part of building this unifying foundation (from an advocacy perspective at least). 'Babbage' would include embedding smart, multi-functional, multi-actuated, micro-mechanical systems in aircraft and rotorcraft structures. It should be noted that work on embedded systems for rotorcraft has been studied for nearly forty years. Such past work includes: free-pitching or indexed rotor blade tips; rotor blade-embedded servo-flaps; on-demand deployment of blade airfoil slats; variable/actuated blade airfoil camber; on-demand trim tabs for blade airfoils; and last but not the least, active and passive blade twist. Despite these earlier studies the full potential of 'smart,' multifunctional, with embedded-actuator, rotor and vehicle structures has still not been adequately explored. This is why a new field of study centered around the 'Babbage' concept will, hopefully, expedite synthesis on old and new concepts and technologies into a unified technical framework. Further, beyond smart, embedded rotor-blade actuators, new rotor design and manufacturing approaches should continue being developed to go beyond the SOA of composite rotor blade construction to include a combination of additive manufacturing, advance composite layup, and multi-part sensors, processors, and micro-mechanical systems. These might even include the speculative addition of 'clockwork'-like Legos™ and other multifunctional structural building-blocks and mechanical systems.

Figure 18. Indexed-Tip Proprotor (Ref. 26)

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[2] In recognition of Charles Babbage, the inventor of the first general purpose mechanical computer, the 'Difference Engine.'

Space and aeronautics synergy (in addition to planetary rotorcraft)

Rotorcraft expertise could be applied to surrogate lander development as well as Vertical Motion Simulator (VMS) simulations of lunar and planetary landers (some of which has already occurred in past work). Further, rotorcraft expertise could also be applied to rotary-wing decelerators (for Earth reentry or planetary entry). Rotorcraft expertise could also be applied for flight dynamics and simulation work for development of cold-gas thruster 'drones' for airless planetary bodies. Rotorcraft expertise could be applied to the design of aeroassist/aerobrake 'coaxial rotor' orbiters (rarified gas analysis), e.g., Ref. 27. Finally, rotorcraft expertise could also be brought to bear on the development of propeller-driven planetary fixed-wing airplanes, e.g., Ref. 28).

Figure 19 further summarizes some of these opportunities for aeronautics and space community synergy.

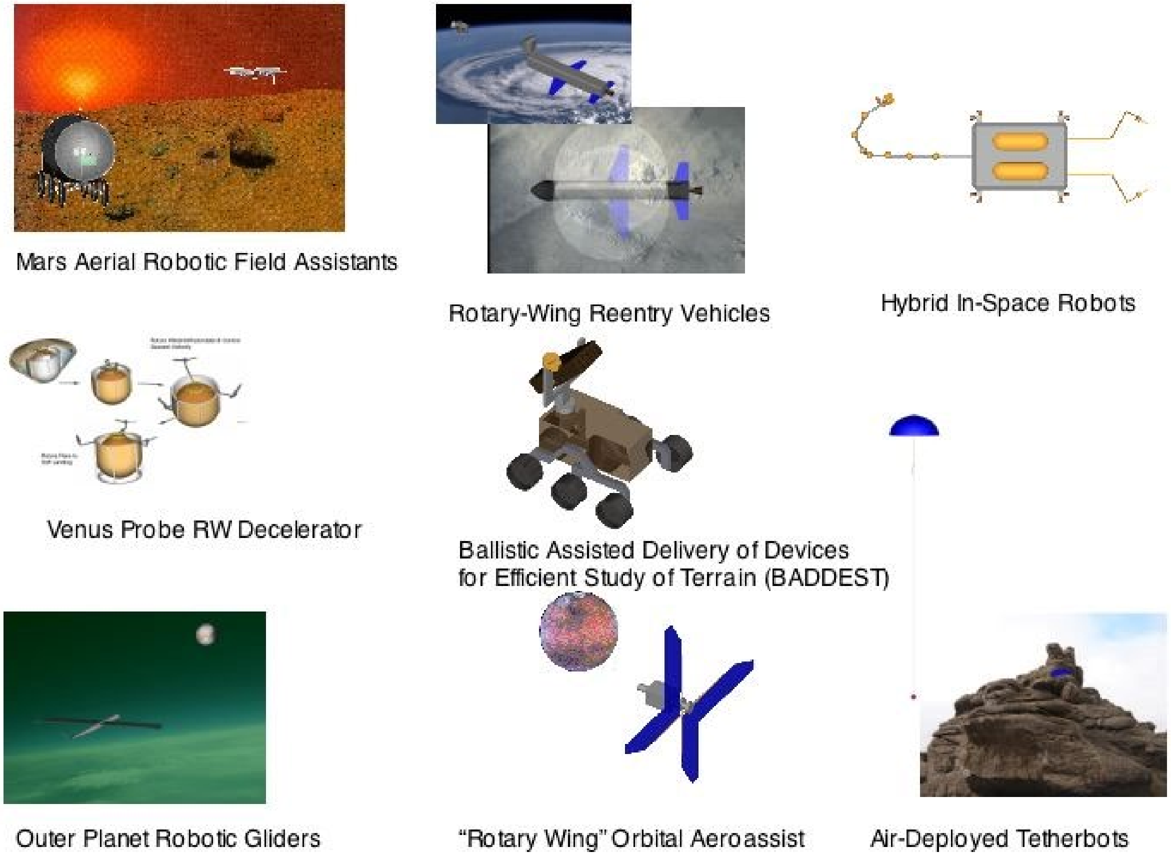

Figure 19. Possible space and aeronautics synergy

Emerging areas of system analysis

Future rotorcraft system analysis efforts will need to begin to try addressing the following analysis problems: autonomy, intelligent systems, and robotics design considerations; livability metrics included in conceptual design refinement/optimization (how are these aircraft going to make our cities and/or rural communities more livable); accessibility considerations in vehicle design; complete life-cycle and system-of-systems considerations; sustain aviation design requirements; factoring in wholly new application domains and technical disciplines and disparate/hybrid technologies.

Figure 20 reflects one possible approach to defining and implementing a 'system analysis as applied to autonomy' methodology.

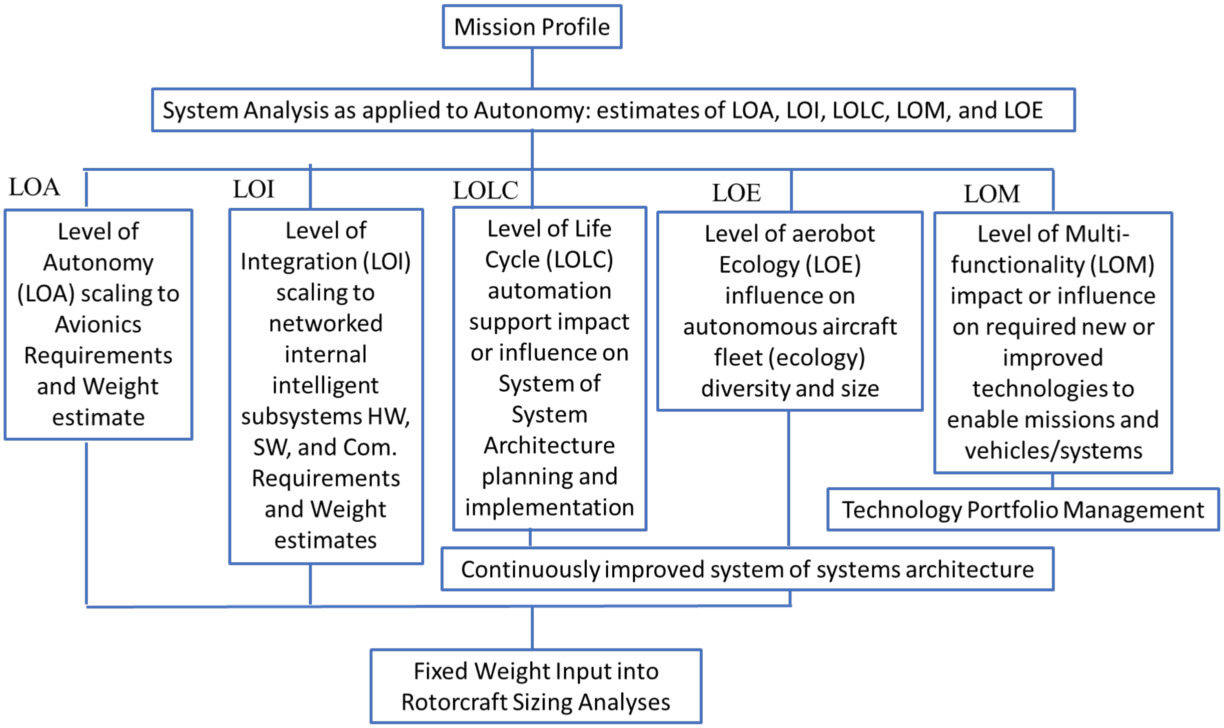

Figure 20. New system analysis approaches required: System Analysis as applied to Autonomy (SAS)

The aerospace community needs to actively fight against the perception that aircraft design – and systems analysis and engineering – are only evolutionary in nature from this point forward. To combat this perception, it is necessary to not only explore new aerial vehicle concepts and new technologies, but it is also necessary to develop (as emphasized in the theme of this paper) new fields of study and application domains that respond to largely unaddressed societal problems. But this, in turn, dictates the development of new system analysis and system engineering tools that encompass new performance requirements, constraints, and success criterion metrics that are novel in nature as compared to the tools and metrics typically used in aerospace analysis.

Asymmetry in aircraft/rotorcraft design

After several decades of CTOL and VTOL aircraft development, most (both commercial/civilian and military) aircraft have begun to look all the same. For rotorcraft, most vehicles are single main rotor and tail rotor helicopters. For commercial aircraft, the conventional tube and wing configuration with four or fewer turbofan engines dominates. Periodically, new types of commercial aircraft designs have been proposed and studied – the recent blended-wing-body (BWB), Ref. 30, and the truss-braced-wing (TBW), Ref. 31, concepts come to mind – and, of course, there are tandem and coaxial helicopters (and tiltrotor aircraft) flying in addition to SMR helicopters. But there is a continued need for aircraft design innovation.

This study considers the implications of intentionally building in geometric (or configurational), structural, dynamic, and mechanical asymmetry into aerial vehicle designs. This suggests, for example, early asymmetric aircraft such as the Blohm and Voss BV141 and Rutan/Scaled Composite's Boomerang aircraft. This is not just about making aesthetic choices in aerial vehicle configurations though. The technical focus of this field of study should be on assessing whether intentional asymmetry in vehicle designs can enable unique flight performance benefits that otherwise symmetrical designs cannot readily achieve. The goal of this field of study should be to promote the development of a unified aerial vehicle design philosophy that embraces asymmetry. The initial steps toward developing such a design philosophy lies in summarizing a few specific vehicle conceptual designs (some previously reported in the literature and some for the first time) that embrace asymmetry. Accordingly, this paper summarizes some of the asymmetric vertical lift aerial vehicle concepts that could be explored. Most of these aerial vehicle concepts exhibit configurational asymmetry and not the other three types possible. (The four types of asymmetries are: configurational, structural, dynamic, and mechanical.)

A few key questions need to be considered:

- What is asymmetry?
- Why and when should asymmetry be adopted in aerial vehicle configurations (with special emphasis on vertical lift aerial vehicles)?
- How can be asymmetry be embodied as a rotorcraft design philosophy?
- What is the potential power of asymmetry as an enabler of wholly new vehicle designs, missions, and applications?

At this introductory point of discussion of 'asymmetry in design,' it is more crucial to define an expansive design space than to deep dive into analysis of individual conceptual designs.

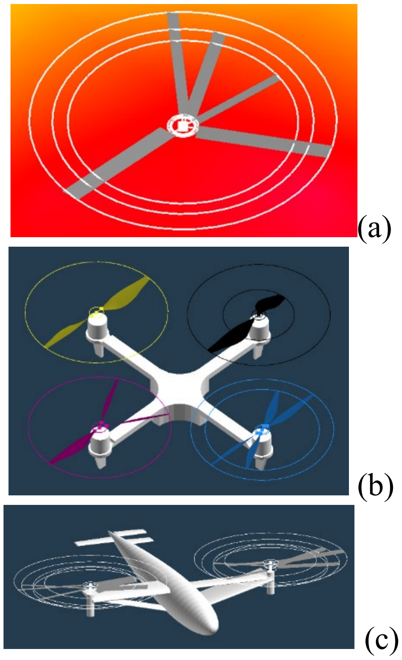

Figure 21. Asymmetry: (a) 'Thistle' rotor, (b) multirotor with 'Thistle' rotors, and (c) 'Nettles' aerial vehicles

UNIFYING THEMES INHERENT IN THESE NEW APPLICATION DOMAINS

As noted earlier, the unifying themes for these new application domains are twofold. First, expanding research communities' conception of what rotorcraft and aerospace, in general, might aspire towards as to addressing societal problems beyond that of the traditional/well-known transport of people, goods, and services. And second, advances in key technologies are also paving the way for innovation: i.e., autonomous and/or intelligent system technologies; robotics, and GNC (guidance, navigation, and communication); all-electric and hybrid-electric propulsion, battery and/or fuel-cell, and power electronics; variable geometry and/or modular rotorcraft subsystems or vehicles.

Figure 22 outlines one possible approach to methodically proceed from identified societal problem to vehicle concepts and technologies addressable by the rotorcraft community.

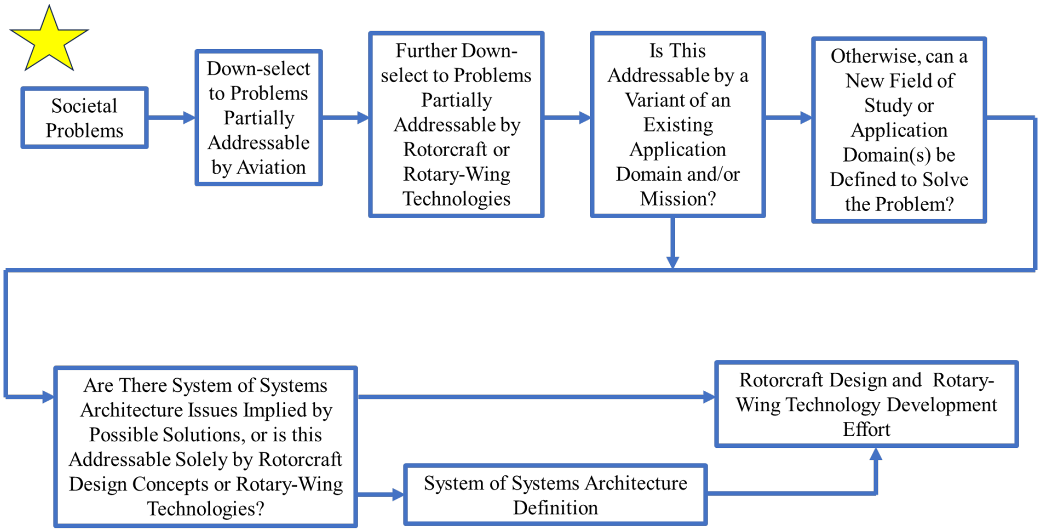

Figure 22. One notional approach to go from societal problems to realizable systems architecture, or vehicle design, or technology investigations

In many of the presented suggestions for new fields of study and/or novel application domains for rotorcraft, there is inevitably going to be some overlap between the presented 'fields' and 'application domains.' Figure 23 illustrates some of that inevitable overlap.

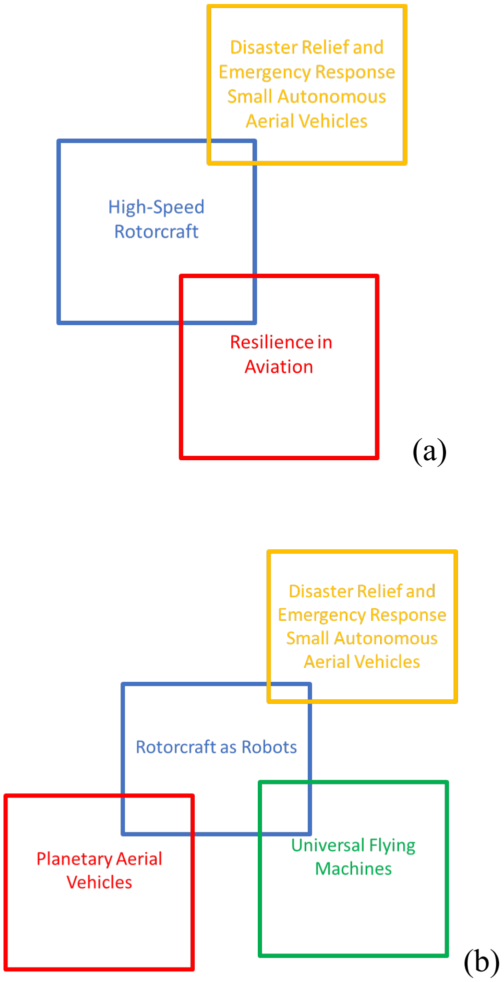

Figure 23. Certain inevitable overlapping between fields of study

MOVING FORWARD TO ENABLE NEW APPLICATION DOMAINS

New mission and vehicle concepts (not just the ones summarized in this paper) are required to identify new application domains. Novel technologies will need to be developed as well to help realize the new mission and vehicle concepts necessary for future application domains.

As much as this is a paper summarizing a perspective of what the future of rotorcraft research and development might entail, this paper is a call to the rotorcraft community to think expansively and innovatively beyond the traditional rotorcraft missions and markets and to consider additional future opportunities.

There are at least two methods of defining new missions for future rotorcraft: a classic mission-centric approach and, alternatively, a vehicle- or technology-centric approach. Figure 24 is a simple illustration of those two approaches and how, in engineering practice, there can be a switching back and forth between those approaches.

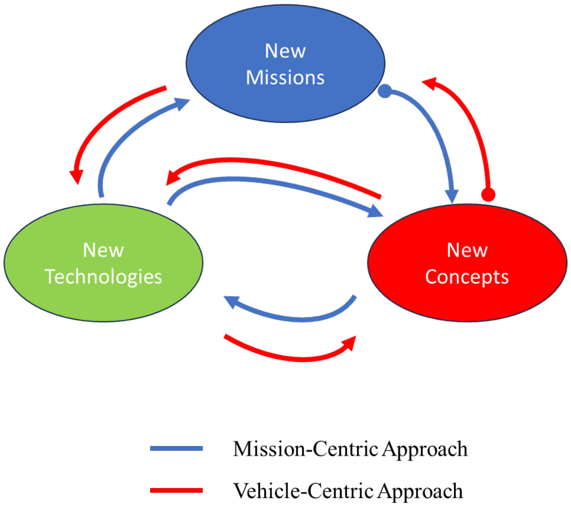

Figure 24. Mission- versus vehicle-centric approaches to defining new missions for future rotorcraft.

REACHING OUT AND BUILDING NEW RESEARCH COMMUNITIES

As noted early, much of the work identified in this paper has stemmed from over two decades worth of research at NASA Ames Research Center. In addition to that body of work, in parallel, other researchers both within the rotorcraft community and outside of it (e.g., robotics researchers), have been also exploring similar alternate application domain research themes.

For the rotorcraft community to successfully engage with some of the emerging fields of study and application domains summarized in this paper, it will be essential to network and collaborate with nontraditional aerospace research communities and other potential future stakeholders. Besides the obvious rotary-wing expertise that the rotorcraft research community could bring to these new applications, the unique mission-focus of aerospace technologists and developers may very well be the critical missing element necessary to address key societal problems that might be more amenable to aviation solutions than currently recognized.

CONCLUDING REMARKS

Applying rotorcraft technologies into new application domains will be an essential element of future growth in the rotorcraft community (industry, academia, and government). Several application domains are suggested in this paper, along with representative sample mission and vehicle concepts.

This paper seeks to inspire a new generation of rotorcraft researchers and developers to consider mission application domains outside the well-explored conventional uses of rotary-wing technologies. The result could potentially see a significant expansion in the overall size of the rotorcraft aviation sector. Exploring these novel mission application domains will likely require collaboration between the rotorcraft community and other research communities, such as roboticists and information technologists, and new/emerging end-user communities.

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ACKNOWLEDGMENTS

This work is for the aerospace engineering innovator. This work is also for the NASA and U.S. Army rotorcraft research community at NASA Ames Research Center. In particular, the inspiration of Mr. Robert Stroub (Ret. NASA), Mr. Edwin Aiken (Ret. NASA), Dr. William Warmbrodt (Ret. NASA), Dr. Chee Tung (Ret. U.S. Army), and Dr. Robert Ormiston (Ret. U.S. Army) is gratefully acknowledged. The development of the mid-fidelity CFD software tool, RotCFD, by the late Prof. Ganesh Rajagopalan of Iowa State University is gratefully acknowledged. Finally, in memoriam, Anne McCracken.

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