NASA/TM—2025–0010330

# Universal Flying Machines (UFM): Modular Multi-Rotor Configurations Integrated into Two- and Three-Dimensional Assemblies

*Larry A. Young*
*Ames Research Center, Moffett Field, California*

**December 2025**

# NASA STI Program ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2025–0010330

# Universal Flying Machines (UFM): Modular Multi-Rotor Configurations Integrated into Two- and Three-Dimensional Assemblies

*Larry A. Young*
*Ames Research Center, Moffett Field, California*

National Aeronautics and
Space Administration

*Ames Research Center*
*Moffett Field, CA 94035-1000*

**December 2025**

This report is available in electronic form at

http://ntrs.nasa.gov

# Universal Flying Machines (UFM): Modular Multi-Rotor Configurations Integrated into Two- and Three-Dimensional Assemblies

Larry A. Young
Aeromechanics Office
NASA Ames Research Center
Moffett Field, CA 94035

**Abstract**

A considerable amount of research has been focused on the use of robotic swarms (whether they be uninhabited ground vehicles (UGV), uninhabited aerial vehicles (UAV), uninhabited surface vehicles (USV), etc., or other types of mobile robots) to accomplish various types of missions and applications. A smaller body of research has examined physically linking (either semi-permanently throughout a mission or temporarily coming together or separating mid-mission) together aggregates, or 'constructs,' of such modular robotic 'elements.' These constructs and their constituent individual robotic elements are collectively referred to in this work as 'universal flying machines' or UFM. This work attempts to lay the foundation on which UFM research may be built upon in the future by both the rotorcraft and the robotics communities. First, a set of definitional requirements and/principles are defined. Next, a non-exhaustive notional set of application domain(s) for UFM are presented. Then an initial classification system for both UFM elements and constructs is outlined. Finally, a series of notional element and construct concept examples are presented by way of illustrating the broad design space represented by the universal flying machines field of study.

## Nomenclature

| | |
|---|---|
| COTS | Commercial-off-the-shelf |
| HIGE | Hover in ground effect |
| HOGE | Hover out of ground effect |
| LOCC | Level of construct complexity |
| LOCCA | Level of construct control authority |
| LOMCCA | Level of construct 'machine' control authority |

| | |
|---|---|
| LOEC | Level of element complexity |
| UAV | Uninhabited aerial vehicle |
| UFM | Universal flying machine |
| UFME | UFM element |
| UFMC | UFM construct |
| UGV | Uninhabited ground vehicle |
| USV | Uninhabited (water) surface vehicle |
| UTM | Universal Turing machines |

**Contents**

## Introduction

What will the future of rotorcraft look like? It is always crucial to consider how to continuously grow an industry, otherwise it might risk becoming stagnate or, worse, irrelevant. Historically or traditionally, the rotorcraft industry has been dominated by the defense and civil security markets, with some small but important civil applications. It should be noted that the promise of the emerging urban air mobility, also known as eVTOL, or air taxis, market could result in substantial expansion of civil aerial transportation applications for rotorcraft. Reference 1 sought to address this broader question of possible new future applications for rotorcraft that might grow the overall industry. Some of the possible application domains introduced in Ref. 1 were those that relied on the 'Universal Flying Machines' (UFM) concept.

The current study leverages a multidecadal body of work by many researchers and developers. First came autonomous (or remotely piloted) aerial vehicles, e.g., Refs. 2-9, then swarms, e.g. Ref. 10, then 'rotorcraft as robots,' e.g., Refs. 1 and 11-17, followed by modular distributed rotorcraft (e.g., Ref. 18), and now the concept of universal flying machines, e.g. Ref. 1. This current work seeks to advance the concept of UFM and the possible applications to which it might be best suited. The first question to address, though, is: what are universal flying machines?

Alan Turing revolutionized the nascent field of computer science by conceiving an abstract computational model (circa, Ref. 19) of what has become known as Universal Turing Machines (UTM). All conventional, non-stochastic/deterministic computational machines can be described in terms of UTM. This report proposes that there is a loose inspirational/aspirational analogy between Universal Turing Machines and what is referred to in this report as 'universal flying machines.' In part, the term "universal flying machines" evokes the bygone age of early aviation pioneers. A new age of aviation pioneers wherein wildly creative and speculative "inventing" ran rampant during the early days of the field of aviation. An age inspirationally reborn anew with the adoption of the UFM paradigm suggested in this paper. The result of this study is very much intended to inspire a new generation of aerospace innovators to push the boundaries of aerial vehicle design as well as the overall concept of 'rotorcraft as robots', e.g. Refs. 11-12.

In many ways this is a follow-on study to – or an extension of – the work presented in Ref. 18. The objective of this work is to begin to explore the intermediate design space between swarms, to modular, partially integrated/assembled systems, to fully integrated machines or aircraft. Specifically, the objective is to explore the world of universal flying machines as formed by individual elements (systems and vehicles) and constructs (which are comprised of assembled collections of elements).

## Swarms versus Constructs

A considerable body of work, e.g., Ref. 10, exists with regards to swarms of robots, aerial or otherwise. However, less work has been focused on the notion of multiple robots structurally intertwined or semi-integrated (if only for a short time with or without limited collective versus individual robotic subsystem functionality and/or 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.' Nothing in this terminology precludes swarms of robots forming and decomposing (or, rather, assembly and disassembly) from swarms to constructs, back and forth upon need. Nothing in this notion of construct precludes the intertwined/semi-integrated multiple robots to be passive or stationary during integration. Nor does this definition preclude the possibility that the integrated construct has unique collective mobility, enhanced, or transformed, actuation/manipulation capabilities – or any other type of collective versus individual element robotic functionality. Ideally, formation and/or decomposition of constructs from elements should happen without external assistance either manually from people or from other, 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/nonreversible process. However, 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. Without this one absolute requirement, the assembly of vehicles is just a free flying ‘swarm’ or, alternatively, it is a single (overly) large (and complex) multirotor vehicle. The intent then is to make UFM something different and more powerful in terms of mission capabilities.

If constructs were statically unstable (from gravity loads, for example), the decomposition, or disassembly, of the construct to elements might be easily implemented if the locking mechanisms that tied the elements together when formed as a construct were released. The construct would reduce to a ‘pile’ of elements that then could be individually self-mobilized as elements to the level of being dispersed as required. The dynamic instability of constructs might also be utilized to decompose, or disassemble, constructs into individual elements. As noted before, such static/dynamic instabilities would unlikely be used to form constructs from elements; the process would seem irreversible without external forces and mechanisms. Still, even the decomposition, or disassembly, process for constructs noted would meet the minimum definitional requirement for a UFM.

Such disassembly – or assembly, if that is feasible – need not happen in mid-air, during flight, but can rather (and most likely) happen on the ground. If the disassembly and/or assembly of the construct occurs on the ground – and not mid-air – then the UFM construct still satisfies the definitional requirements (as proposed in this paper) for universal flying machines.

Alternatively, if a two-dimensional construct assembly were considered, if the individual elements are laid out as loosely spaced, nonoverlapping tiles, then vertical flight takeoff/disassembly should be possible, once the locking mechanisms were released. If the UFM elements form a three-dimensional matrixed construct, and if the elements were laid out in layers, then the individual elements could still perform vertical flight takeoff and disassembly layer by layer, from the top of the construct to the bottom.

Several specific examples of constructs and construct missions/applications will now be introduced to go from a rather abstract sense of the overall concept to some tangible, if not pragmatic, realizations of the concept. These examples were especially chosen to emphasize the aerial mobility aspect of the individual robotic systems, the “elements.”

1. A temporary or ephemeral sculpture of ‘mobile” artwork that is self-assembled and then self-disassembled, or transformed, from a swarm of aerial robots. A UFM “construct” version of drone-swarm light shows.
2. A self-assembled large-scale solar array farm that follows the sunlight.
3. Temporary self-assemble architectural structures for special (semi-) outdoor events that occur occasionally or periodically at various locations; (Like awnings/coverings that are composed of many “flying parasol” aerial robots).
4. Lake, or other body of water, surface covering along the shorelines to combat algal/bacterial blooms through reduced sunlight and/or localized chemical treatment enabled by the self-assembled UFM littoral surface-cover construct.
5. Temporary self-assembled barriers or barricades for various purposes.
6. Self-assembled, relocatable “sentinel structures” for defense, security, or disaster relief efforts.

7. Hazardous waste treatment of contaminated soil and shores by ground-conforming flat arrays of treatment materials formed from self-assemble constructs of small aerial vehicles/robots.
8. Constructing large-UAVs from small UAVs/aerial robots for enhanced range and mission capability.
9. Small aerial robots self-assemble to floating and surface-mobile water/sea vessels (and vice versa).
10. Small aerial robots self-assemble into large ground-mobile robots (forming for example, a large rolling "tumbleweed-type or tumblebot robotic construct).
11. Farming applications (isolation and/or protective temporary structures "formed on the fly"). On-demand, rapid containment of pests, wind breaks, flooding "sandbags" (though use entrainment/release of water instead).
12. Self-deploying/self-assembling emergency shelters.
13. Creation on demand of large but relatively simple machines using rotors instead of servomotors or linear actuators.
14. Extreme weather resistant (severe winds and/or gusts) aircraft that are constructs with high degrees of symmetry and ability to react to upsets stemming from extreme weather conditions. I.E., aircraft that can exhibit static and dynamic flight stability regardless of attitude/orientation subject to the most extreme of upsets.

The most obvious UFM end-to-end conceptual implementation would be #8 in the above list, wherein large UAVs are constructed from small UAVs.

Swarms can form constructs through some version of assembly, mechanical intertwining, or semi-integration; correspondingly, swarms can be formed from the partial or full decomposition of constructs.

The manufacture of large numbers of small commercial-off-the-shelf (COTS) UFM elements to create large constructs will ideally lead to substantial economies of scale. A UFM element (UFME) as defined in this report is the smallest indivisible system of an overall UFM construct.

A counterexample is now provided of a construct and individual elements that are not universal flying machines. A crane-like rotor-actuated robotic arm is shown in Fig. 1. Though movement of the robotic arm relies on a rotor providing upward and downward thrust (through positive and negative blade collective pitch angle inputs) and rotational movement of the horizontal support arm by inplane forces (through rotor cyclic pitch inputs), no element of the system can individually undergo controlled powered flight. I.e., even if the rotor and its motor(s) were detached from the crane-like horizontal support arm, as there is no anti-torque provision in the conceptual design (as there is shown only a single isolated rotor).

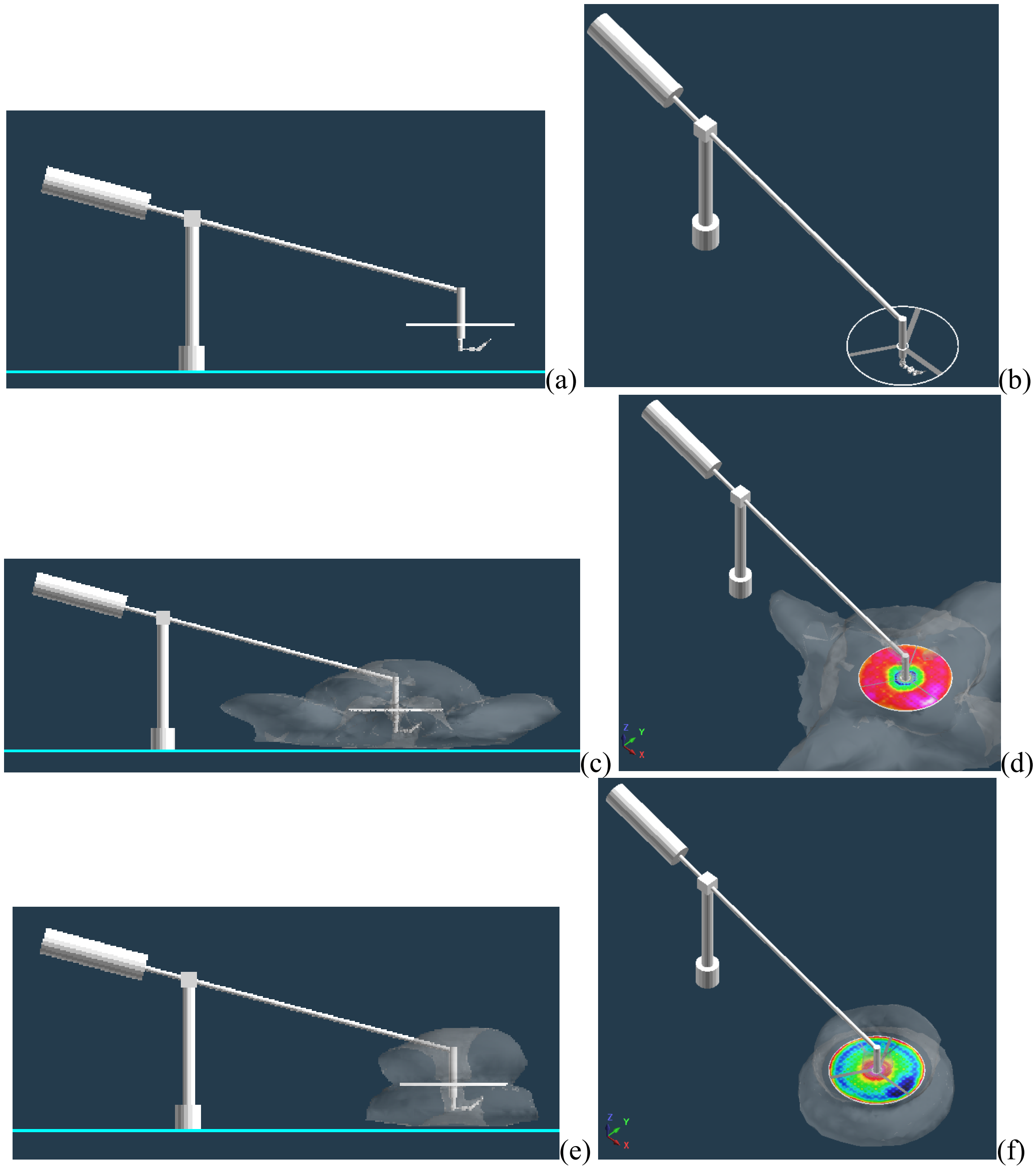


**Figure 1. Crane-like rotor-actuated robotic arm: (a) side view, (b) isometric view, (c), side view with mid-fidelity CFD predictions of rotor wake (thrust up), (d) isometric view with mid-fidelity CFD of rotor wake (thrust up), (e) side view of rotor wake (thrust down), and (f) isometric view of rotor wake (thrust down)**

## Required (and Optional) Features of a Single UFM Element

There can be more than one kind of element in a construct. Not all elements need to have aerial mobility to form a construct that is, in turn, a UFM. Table 1 describes several notional levels of element complexity (LOEC) that a UFM element might have.

**Table 1 – Levels of Element Complexity**

| LOEC | Element Attributes |
|---|---|
| | |
| 1 | Simple, primarily structural, nonflying, non-mobile (either on ground or other surfaces) element |
| 2 | Nonflying but with some actuation/effector capability |
| 3 | Nonflying but with some (other) mobility capability |
| 4 | Flying but with only rpm control |
| 5 | Flying with rotor(s) collective and cyclic pitch control |
| 6 | Flying with acrobatic (flip and fly upside down or other irregular attitudes/orientation) capability |
| 7 | Flying with full-range tiltable rotors (all rotors' thrust can be oriented to maximize construct lift |
| 8 | Flying with all, or partial, rotor flight control capabilities but with limited construct (small number and relative orientation/integration of elements) capability |
| 9 | Flying with extensive two-dimensional array construct capability |
| 10 | Flying with limited (partial) three-dimensional matrix construct capability |
| 11 | Flying with extensive three-dimensional matrix construct capability |
| 12 | Flying with extensive three-dimensional matrix construct capability that allows for the additional capability of morphing or transforming (while nonflying) |
| 13 | Flying with extensive three-dimensional matrix construct capability that allows for morphing and transforming while flying |

There can be heterogeneous rotors (in terms of radii, blade count, blade planforms, and disk loading) included in each element. Further, there might be morphing or transforming of constructs, which may or may not include 'stretching' of elements at the attachment/connection/interlocking-mechanism points. This stretching in a quasi-topological sense reflects the possible use of 'soft' versus 'hard' versus 'stretchable' (i.e., elastic with large displacement capability) hinges and other attach points along element edges and vertices.

Figure 2 illustrates one of the simplest rotor-based UFM elements: a single rotor with inclined/angled vanes embedded in the rotor wake for anti-torque capability. This approach works fine for near-hover conditions but becomes a more challenging design approach with increasing edgewise forward-flight.  Figure 2c-d show how the elements of Fig. 2a-b can be combined into a simple UFM construct of different geometries.

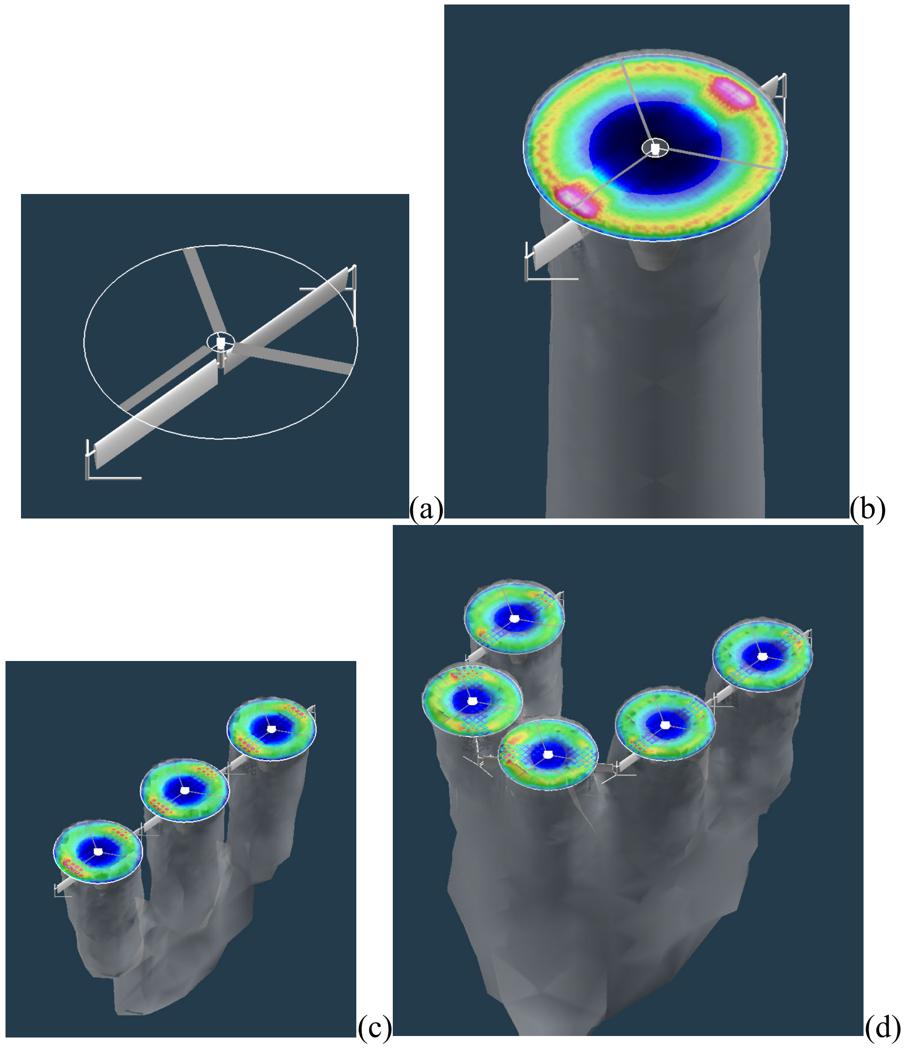


**Figure 2.  UFM Elements can have any number of rotors (and means of anti-torque): (a) single rotor with vanes in rotor slipstream for anti-torque, (b) single element mid-fidelity hover predictions, (c) CFD hover predictions of a small construct formed from the mono-rotor element**

## Required (and Optional) Features of an Aggregate, or Construct, of UFM Elements

Movement of constructs and the actuation or manipulation of their environment can, unlike other robotic systems, be enabled not only by electromechanical actuators, servos, and electric motors but, in the case of UFM constructs, also by the lift/thrust and moments from the collective exercising of the individual UFME rotors, propellers, or other propulsors. This is a powerful capability of UFM constructs; movement, actuation, or manipulation of the surrounding environment of the construct might not otherwise be possible because of the collective limitations of the electromechanical actuators, servos, and motors because of the collective high inertia and weight of the construct.

For those UFME employing rotors, fans, or propellers for individual element three-dimensional mobility, it goes almost hand-in-hand that such rotors, etc., be operable such that one of three modes of operation are available to maximize the flexibility of incorporating UFME into a mobile or flying construct: 1. reverse and forward rotation; 2. or control capability for both positive and negative collective angles and thrust; 3. or the rotors are capable of being tilted to large angles, ideally up to full three-hundred and sixty degrees of rotor tilt. This in turn could result in unique choices in selected rotor blade airfoils (favoring perhaps flat-plate or circular-arc airfoils) and rotor twist distributions (favoring perhaps untwisted blades).

In each construct, there can be heterogenous elements (differences between one element and the others); e.g., Ref. 18. There can be flying and nonflying elements in a construct; this is particularly likely in the case of where a construct forms a simple Archimedean-type machine for nonflight phases of operation (to be discussed further below).

Just as there are ways to try categorization of individual elements, there is also a need to try categorizing constructs. Table 2 represents one approach at attempting to categorize constructs.

**Table 2 – Levels of Construct Complexity (LOCC)**

| LOCC | Construct Attributes |
|---|---|
| | |
| 0 | “Swarm” with loosely organized and minimal system-to-system communication; does not meet the minimum requirements for a construct |
| 1 | “Swarm” tightly organized with high degrees of system-to-system communication; approaches but does not meet the minimum requirements for a construct |
| 2 | Simple construct; meets minimum UFM construct (UFMC) requirements; disassembly only; ‘soft’/elastic interlocking connections, including (A) non-reel-able or (B) reel-able tethers |
| 3 | Simple construct; meets minimum UFMC requirements; disassembly only; rigid/stiff interlocking connections; static and immobile configuration when fully assembled |

| | |
|---|---|
| 4 | Construct with ground locomotion capability when in assembled form; disassembly only |
| 5 | Construct with ground and air mobility when in assembled form; disassembly only from UFMC to UFME |
| 6 | Construct that can morph or transform mid-flight, or on the ground, when in an assembled UFMC form(s); ability to morph is limited in that effectively only disassembly of UFMC to UFME is still only possible |
| 7 | Construct with ground locomotion capability when in assembled form; (repeated) assembly and disassembly is possible while on the ground, by means of (A) specialized ground equipment or (B) self-actuated/self-enabled solely be onboard systems |
| 8 | Construct with ground and air mobility when in assembled form; (repeated) assembly and disassembly is possible while on the ground, by means of (A) specialized ground equipment or (B) self-actuated/self-enabled solely be onboard systems |
| 9 | Construct that can morph or transform mid-flight, or on the ground, when in an assembled UFMC form(s); in addition to morphing/transforming into multiple assembled forms there is also the ability to (repeatedly) disassemble or assemble in (A) on ground or (B) mid-flight; UFME have the ability to fly independently, or as a swarm, in between cycles of assembly and disassembly into or out of UFMC form |

In addition to the approach taken in Table 2, another way to look at the categorization of constructs is the approach outlined in Fig. 3. Here, the focus is on the construct's ability to transform (flying or nonflying) and whether this transformation (assembly and/or disassembly process) is reversible or irreversible (without external application of forces or displacements enabled by external mechanisms and/or external sensors (e.g., element control via Vicon motion tracking systems)).

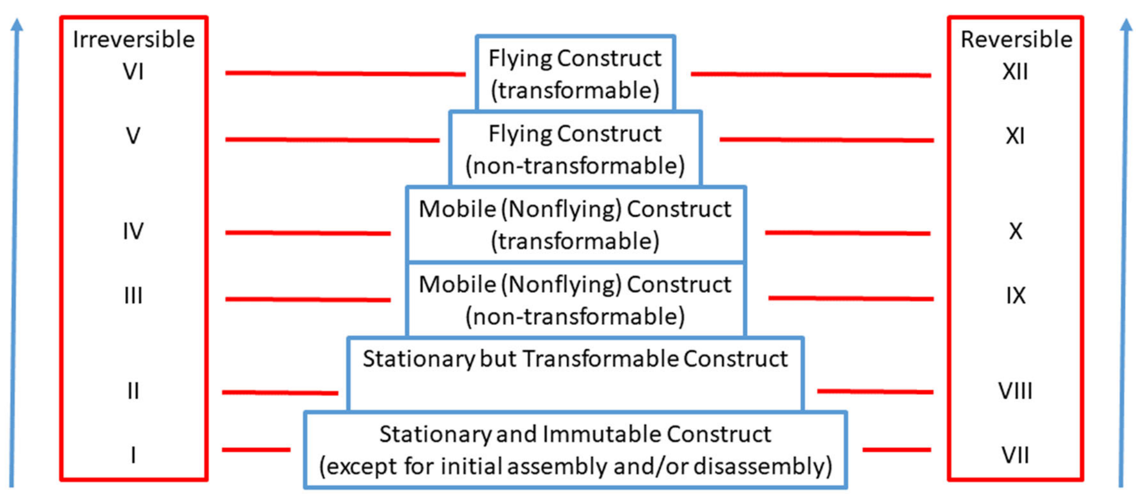



**Figure 3. Classes of, or Classification System for, Constructs**

Inevitably there can be a blurring of the line between a large multirotor vehicle, or single element, and a construct formed of several simpler elements (with fewer rotors).

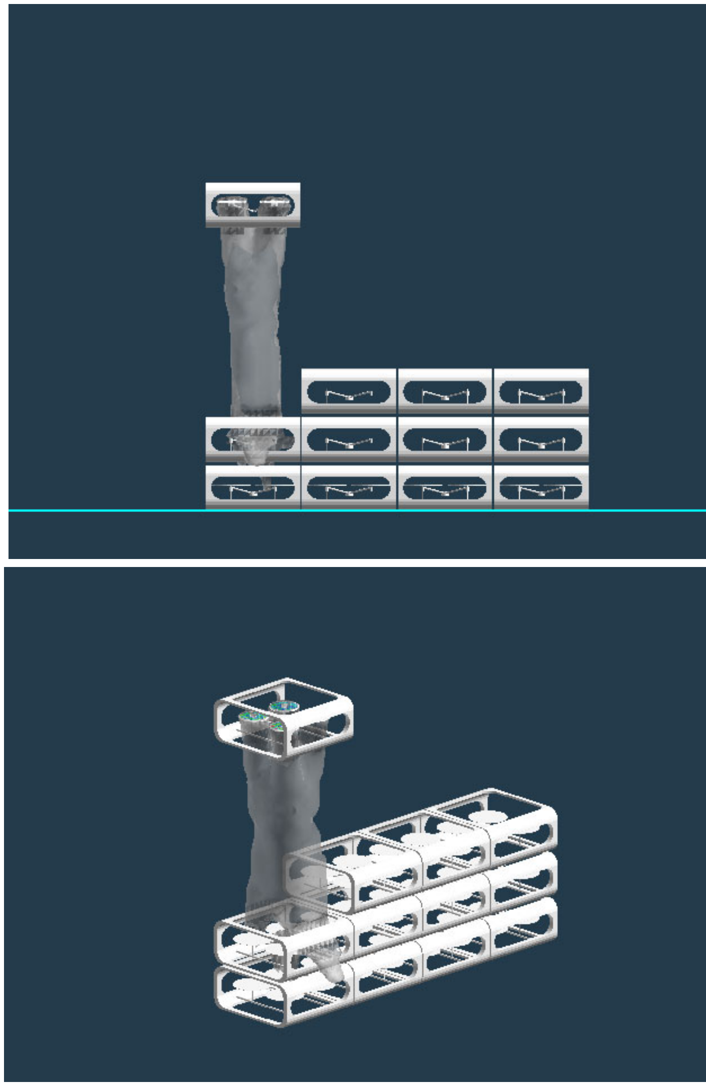
## Potential Application Domains and Associated Missions

As noted earlier, the one absolute requirement of a construct, or specifically a universal flying machine, is that there is the need for transitory formation and decomposition of constructs from elements. Accordingly, missions and applications will be discussed in detail that fully encompass that requirement.

### Predominately Two-Dimensional Assemblies

#### *Stationary*

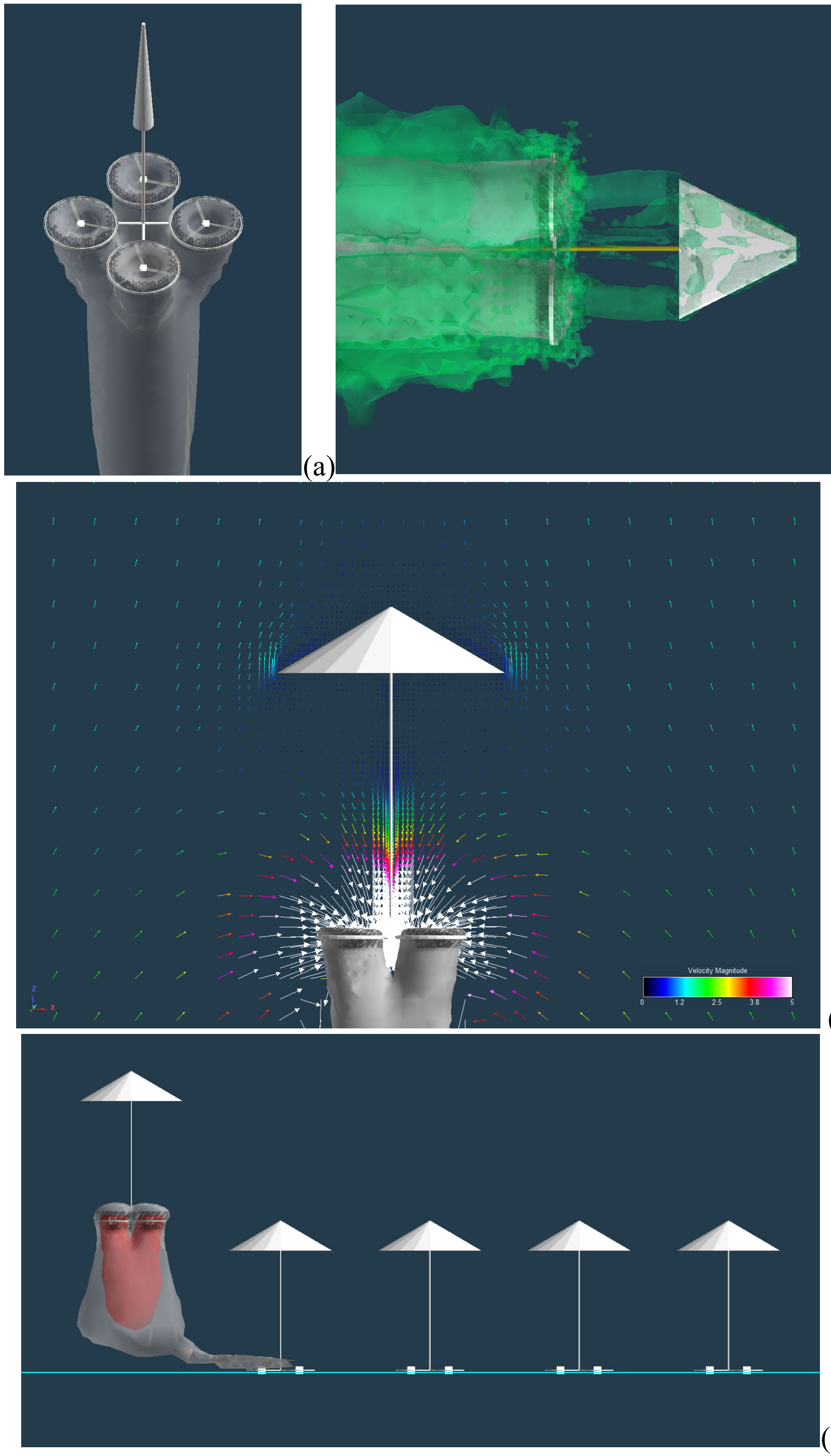
There are several potential applications whereby the transport and construction or assembly of stationary structures via primarily predominately two-dimensional array constructs might be viable. This might be especially true for applications where the placement of temporary structures might make sense, e.g., Fig. 4. This would seem to focus on applications in which there is need for the speed of the emplacement and construction based on high demand, or criticality, for such erection of structures, and an equal demand for the eventual repurposing or removal of such a construct-enabled erected structure. Alternatively, the applications that might support such UFM construct-enable stationary structures are those in which remote and sustained presence of such structures, with the repeated disassembly or assembly into swarms of flying elements for surveillance or scientific/environmental surveys/monitoring is required.



(a) (b)

**Figure 4. Fences/Walls: (a) side view of single element hovering above partial fence construct and (b) isometric view**

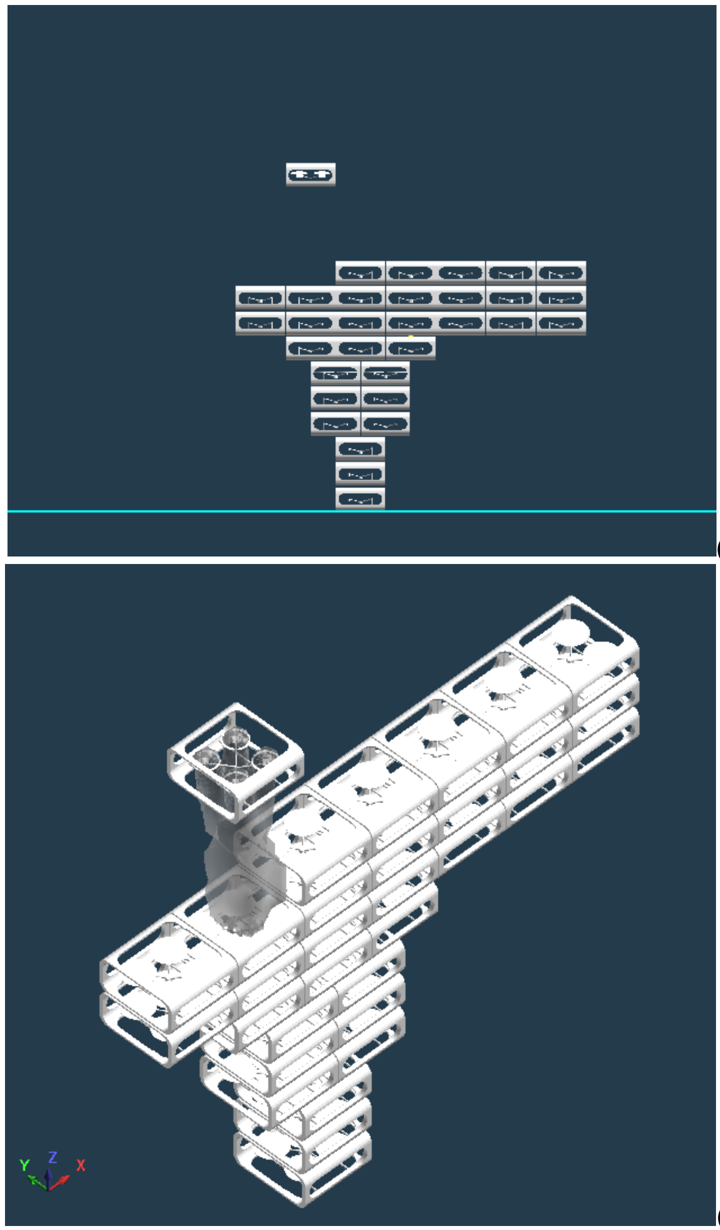
Figure 5 illustrates another stationary 'structure' construct by flying UFM elements: layout of an array of matrix of 'parasols' to act as sunshades for recreational use. This is a somewhat whimsical application but given that providing shade for displaced individuals during emergencies is potentially critical for their health and wellbeing, such an application might one day have serious ramifications. The stability of such flying parasols might be challenging so the ability to fly them like tailsitter aircraft might be one approach to take for their flight. Additionally, small thrusters at the apex of the parasol might be necessary for a restoring moment in case of wind upsets in near hover.




(a) (b) (c) (d)

**Figure 5. Sunshade and/or Ground-Cover Infrastructure Installations: (a) vertical takeoff with parasol closed, (b) forward flight ('tail sitter airplane mode') with parasol deformed to wing/sail-like shape, (c) vertical descent with parasol open, and (d) vertical landing with parasol open and joining a row of stationary parasols**

Figure 6 illustrates a third possible stationary structure – the possible construction, or assembly, of bridge-like structures – from flying UFM elements. Note that plates may have to be overlaid the open cutouts in the elements to allow for the rotor wakes to pass through relatively unimpeded for maximum thrust efficiency and to allow for safe passage of objects being carried across the assembled structure.




(a)

(b)

**Figure 6. Walkways/Bridges**

A UFM construct could be, in an analogous sense, the ultimate ‘free agent’ system. There will be a reoccurring debate as to ‘dedicated assets’ being employed for a particular application or mission versus a ‘free agent’ system. Figure 7 illustrates the loose construction or assembly of a ‘tent city’ from multiple tents carried or integrated into UFM elements.

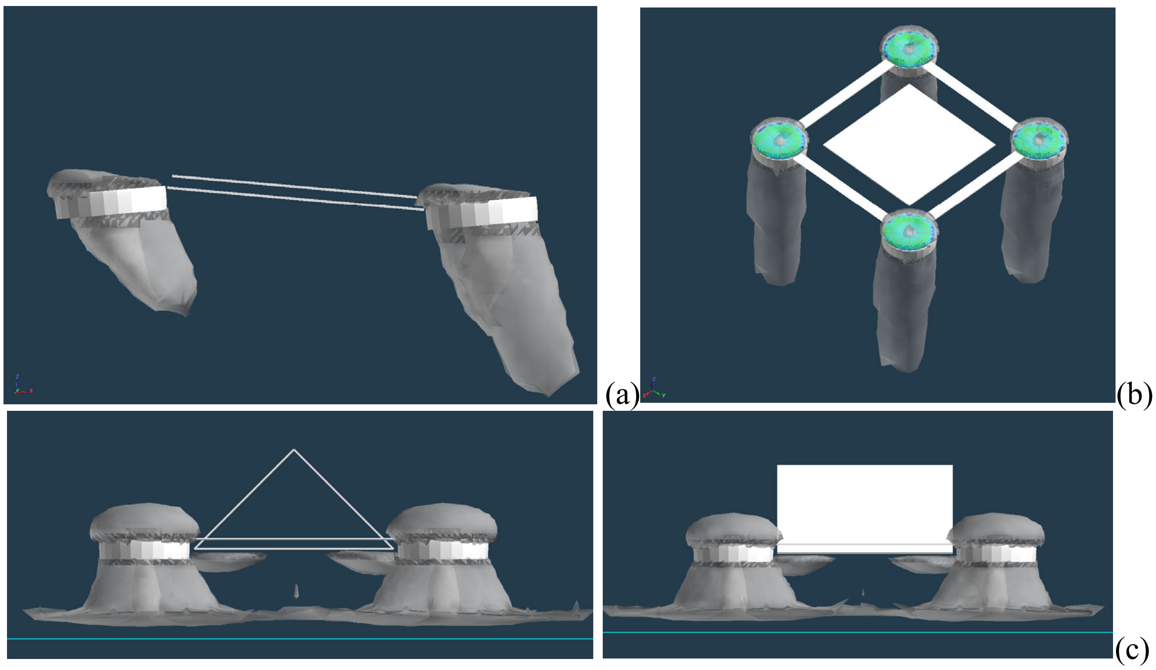



**Figure 7. Camping or Emergency Shelters: (a) with folded tent, flying edgewise forward flight, (b) hovering out of ground effect (HOGE) with folded tent, and (c) hovering in ground effect (HIGE) with popped-up or deployed tent**

Figure 8 is an illustration of a notional flying life preserver which shows how multiple such aerial vehicles in conjunction with multiple preservers can form a raft-like floating platform potentially multiple people. This application is currently being explored by industry and academia, e.g., Ref. 20.

Note that multiple flying preserver elements could be assembled as a construct to yield a larger raft-like rescue device, Fig. 9.

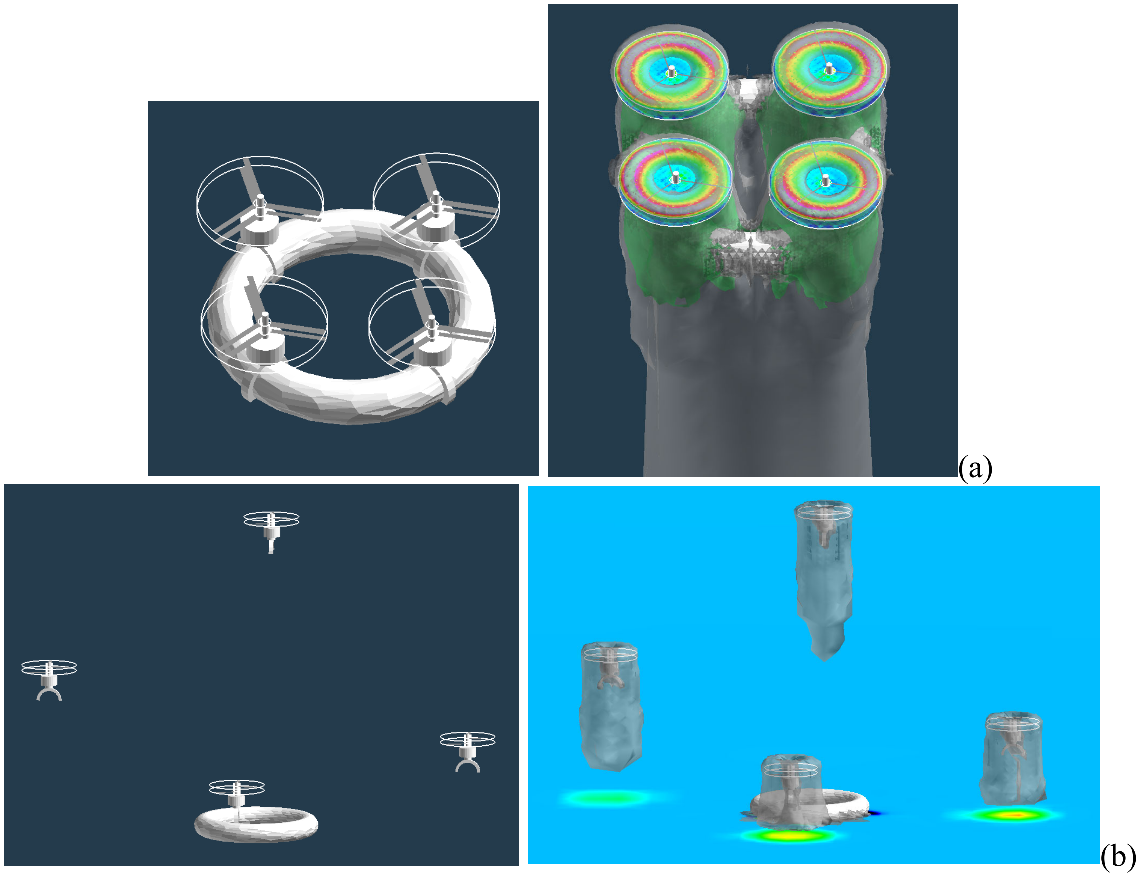



**Figure 8. Emergency Deployment of Water Rescue Aids: (single flying life preserver; one preserver and multiple coaxial flying elements)**

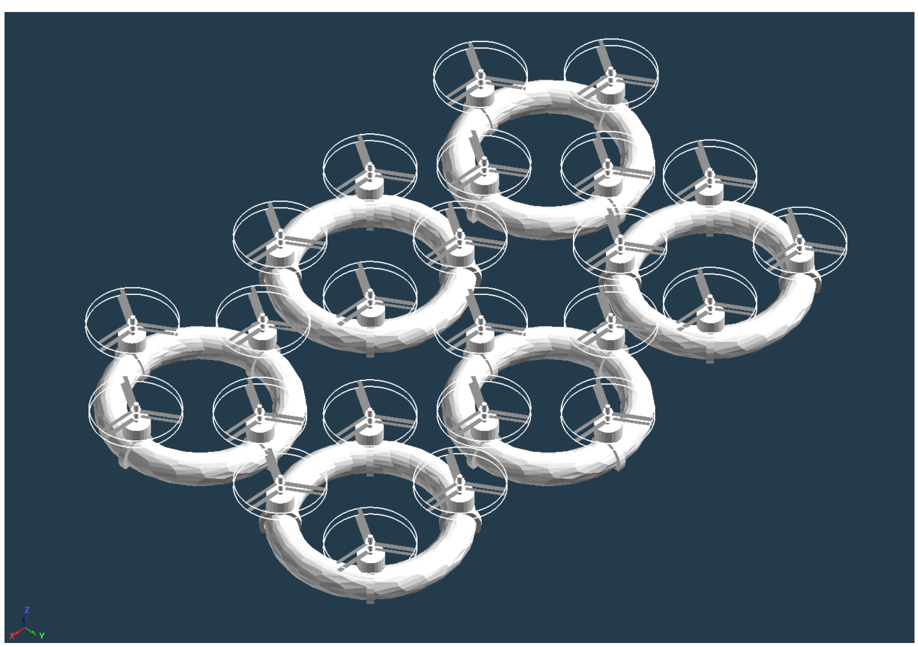
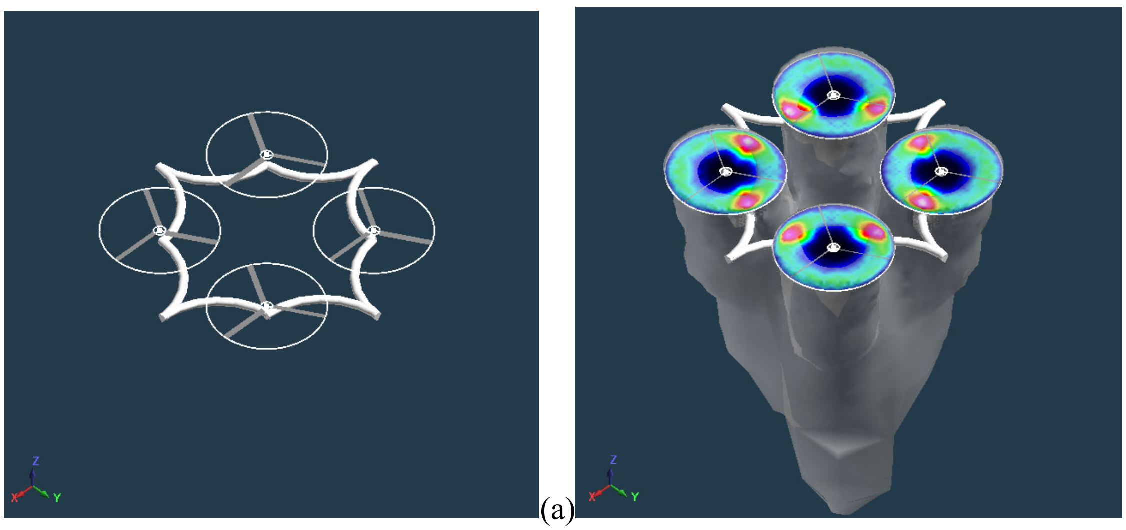


**Figure 9. Emergency Deployment of Water Rescue Aids (life preservers additively form life raft)**

### *Flying*

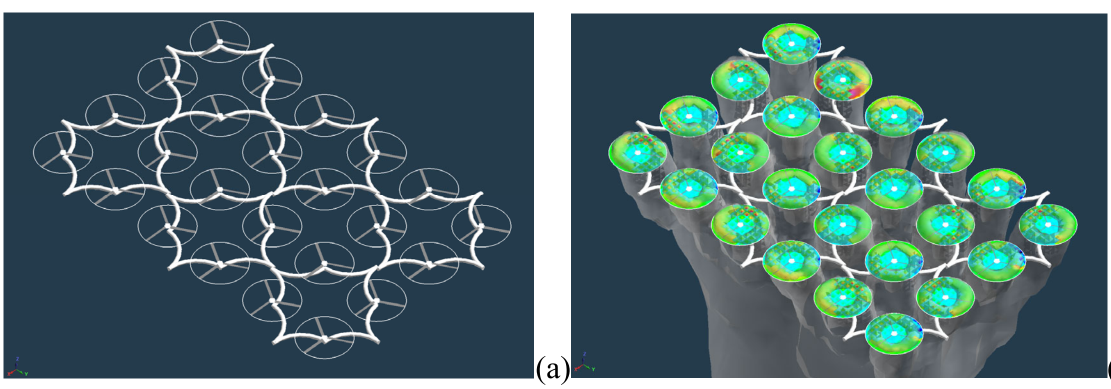
One of the key considerations of the formation of flying constructs is how to efficiently, both from an aerodynamic performance perspective and, equally, from a weight/structural perspective, connect, interlock, and assemble flying elements into flying constructs (whether the constructs are two- or three-dimensional in overall character).

Figures 10-12 illustrate a 'magic carpet' element and construct. The unique geometric pattern shown for the UFM element's nonrotating frame is just one approach to emphasize aerodynamic and structural efficiency.



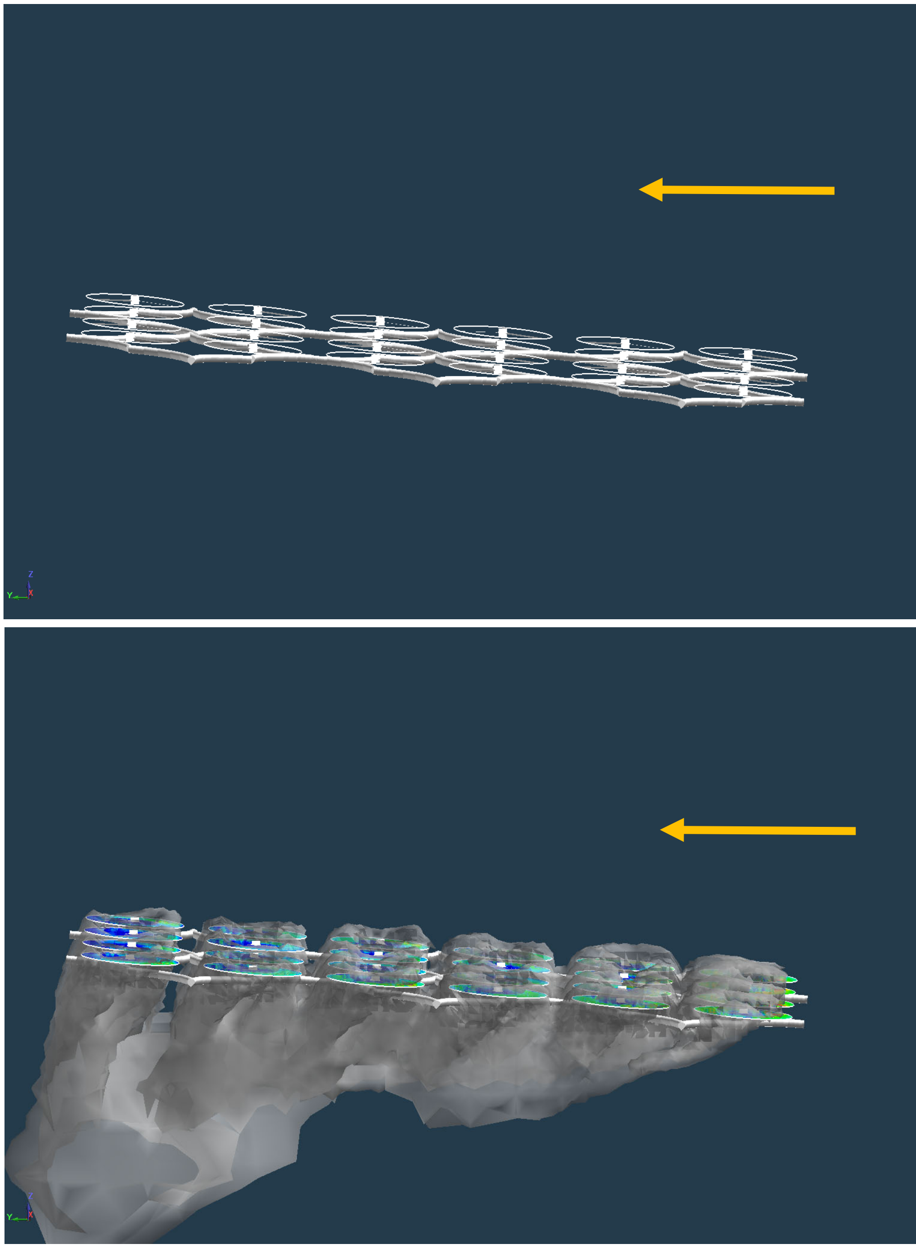
(a)
(b)

**Figure 10. "Magic carpet" element in hover**



(a) (b)

**Figure 11. "Magic carpet" construct in hover**

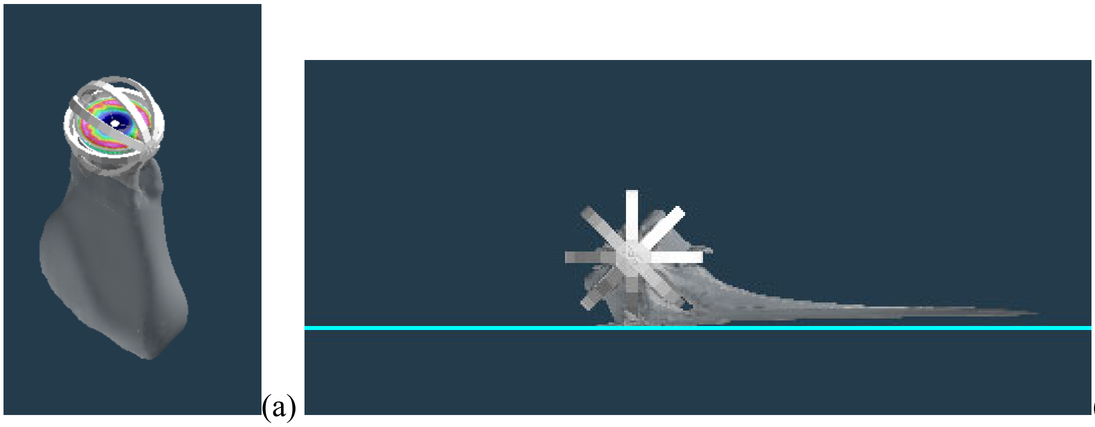


(a) (b)

**Figure 12. “Magic carpet” construct in forward flight**

Another notional flying UFM construct, with hybrid air/ground mobility, are the ‘Beads’ and ‘Pearls’ concepts shown in Figs. 13-15 and Figs. 16-18 respectively. These concept, like the ‘magic carpet’ concept discussed earlier emphasizes an important technical point: i.e., the rigidity or stiffness of the linkages connecting individual UFM elements into the UFM construct can either be soft or rigid, or in between, and can be constant in that stiffness or can exhibit some ability to adjust that linkage stiffness during a mission. The ‘Beads’ and ‘Pearls’ concepts also consider the implications of UFM elements and constructs having hybrid air/ground mobility (HA/GM). There is currently ongoing analogous work using ‘linked together’ small ground mobile robots, e.g., Ref. 21.

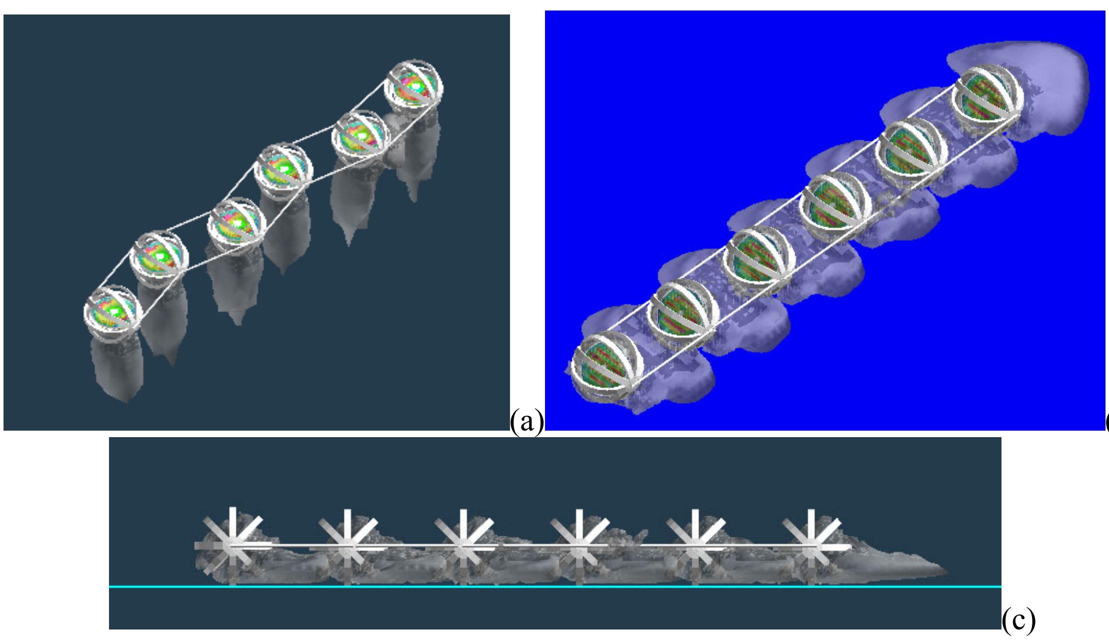
Figure 13 illustrates a notional UFM ‘bead’ element. Similar multirotor systems embedded in a spherical wireframe shell have been studied before in the literature, e.g., Ref. 22.



(a) (b)

**Figure 13. “Beads’ hybrid air/ground mobility robotic system (element) concept: (a) in hover and (b) ground locomotion**

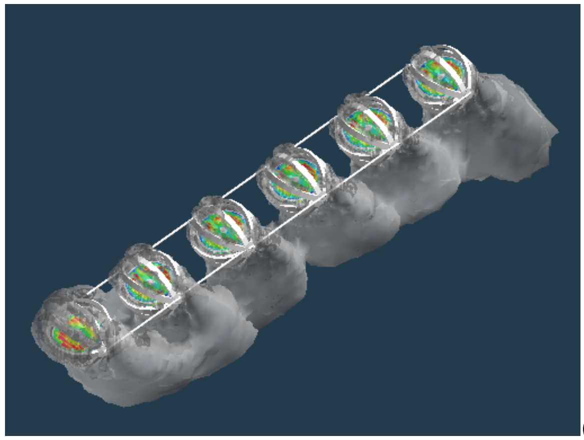
Figure 14 illustrates the ‘bead’ UFME strung together with tethers (or soft/rigid mechanicals links or beams/truss structures) to form a UFMC. The flight dynamics of such tethered or mechanically linked constructs flying is largely an unexplored area of research.



(a) (b) (c)

**Figure 14. “Beads’ hybrid air/ground mobility robotic system (construct) concept (a) flying in hover and (b) ground locomotion isometric view, and (c) ground locomotion side view**

Figure 15 illustrates several beads in a linear array flying together using the mid-fidelity CFD code, RotCFD, e.g. Refs. 23-24.


(a)

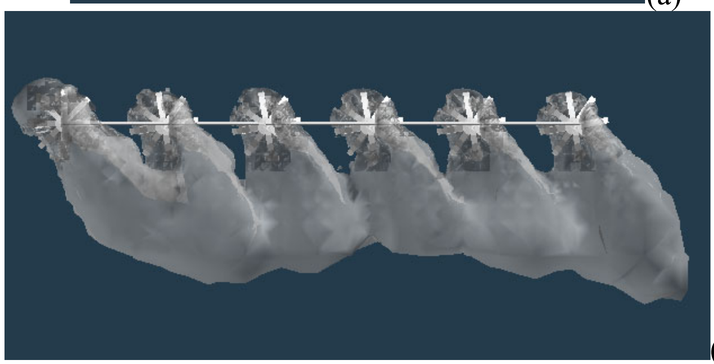

(b)

**Figure 15. Beads flying in edgewise forward flight**

Figure 16 illustrates the ‘pearl’ UFM element. Instead of a coaxial rotor pair as notionally introduced in the bead element discussion, the pearl element notionally can employ side-by-side rotors.


(a)

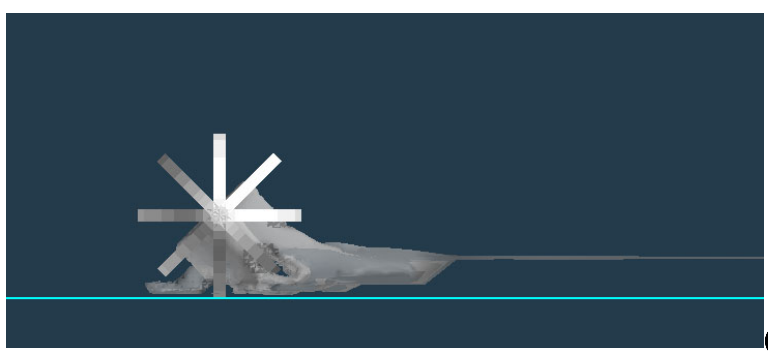
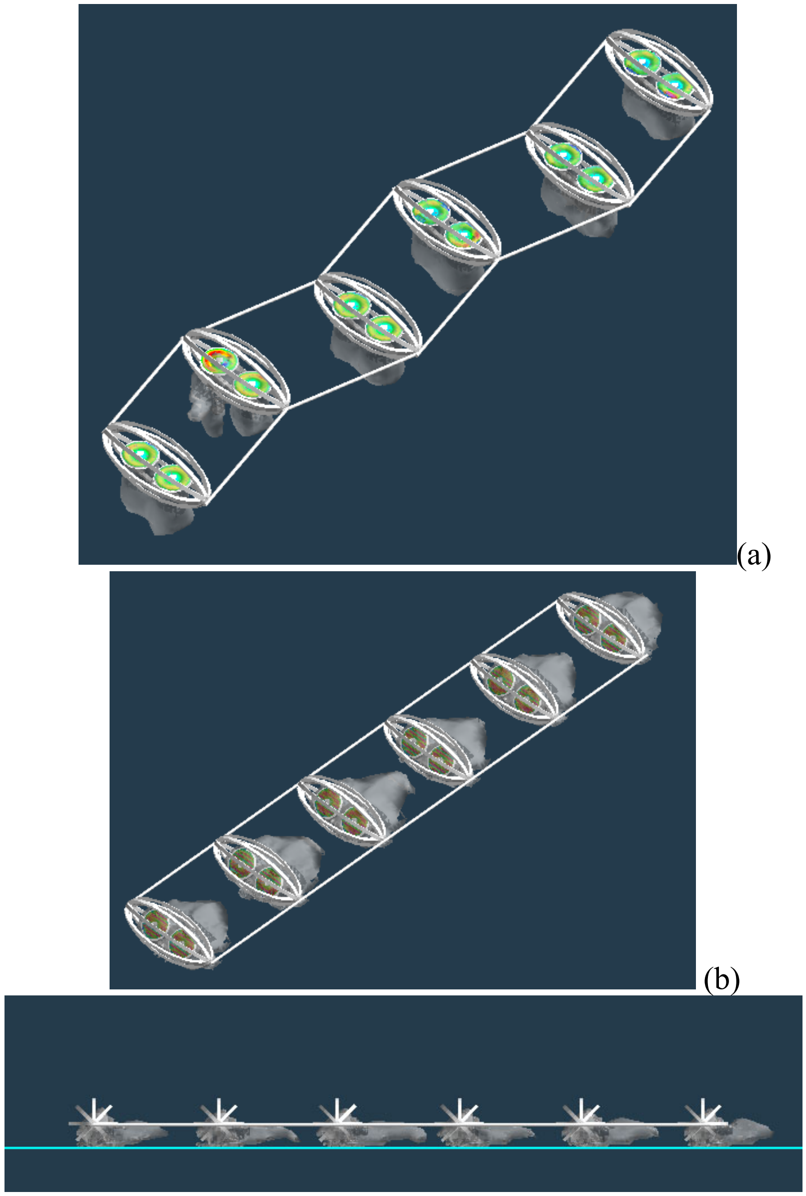

(b)

**Figure 16. “Pearls’ hybrid air/ground mobility robotic system (element) concept: (a) in hover and (b) ground locomotion**

Figure 17a-c illustrates a notional linear array of pearl elements flying tethered together in hover (Fig. 17a) as well as in rotor-propelled ground locomotion (Fig. 17b-c).



(a) (b) (c)

**Figure 17. "Pearls' hybrid air/ground mobility robotic system (construct) concept (a) flying in hover, (b) isometric view of ground locomotion, (c) side view of ground locomotion**

Figure 18a-b presents some CFD flow field predictions (velocity magnitude isosurfaces for the rotor wakes and color contours for the differential pressures across the rotor disks) for the linear array of pearl elements flying tethered together in edgewise forward flight.

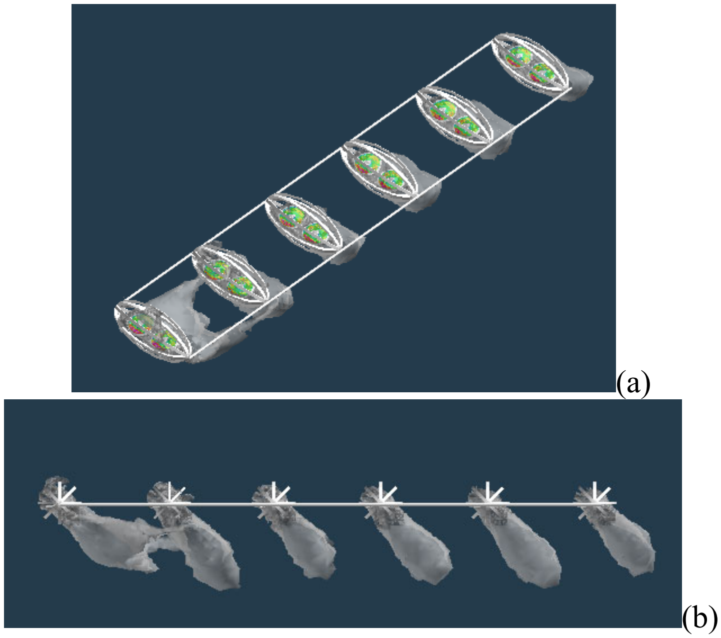
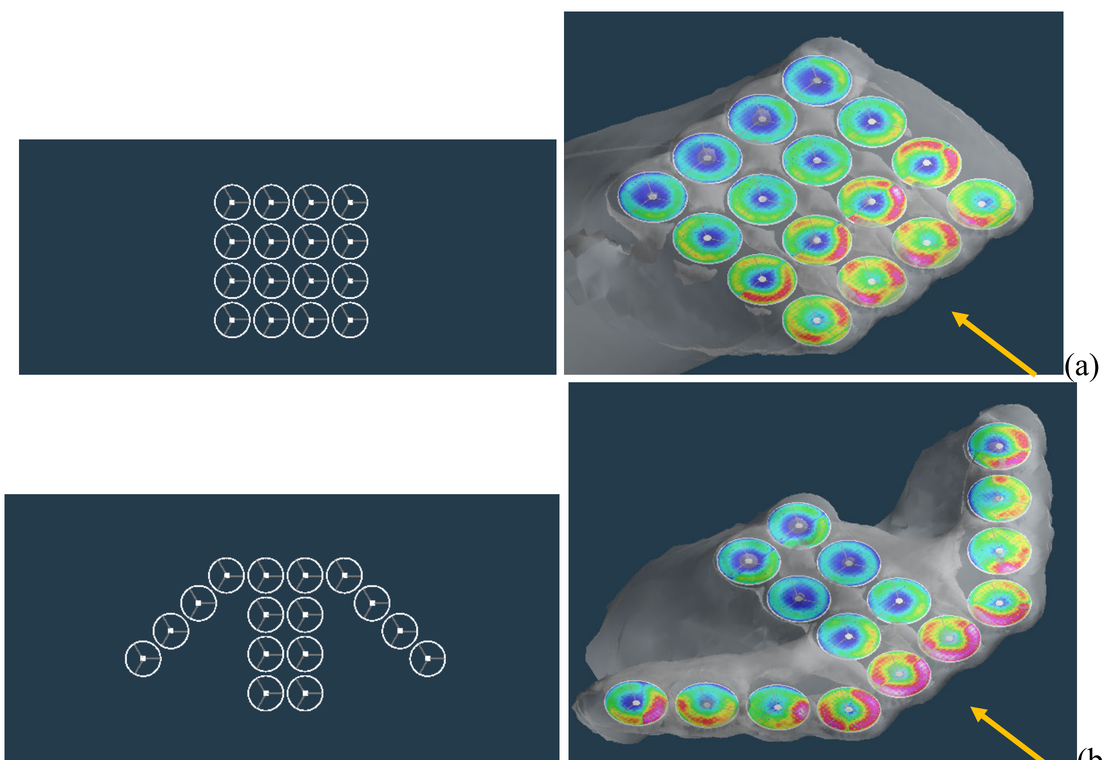
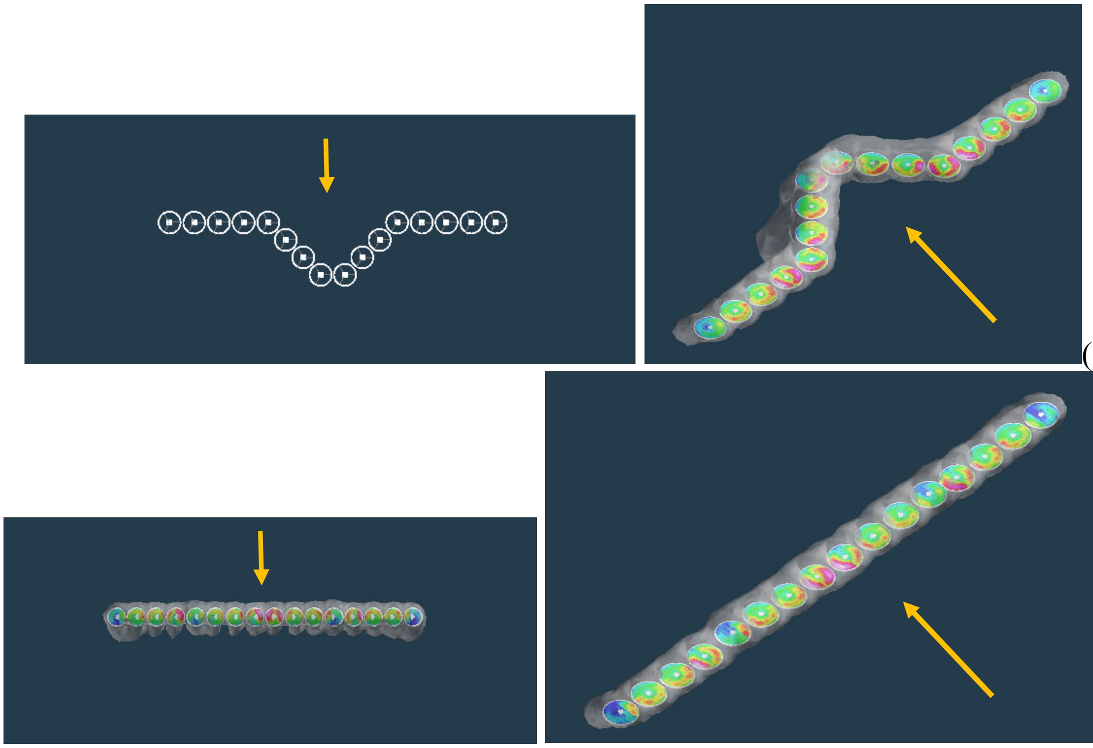



**Figure 18. Pearls flying in edgewise forward flight**

Figure 19a-d illustrates one possible two-dimensional (mid-flight) transforming construct. Reference 18 briefly discussed similar mid-flight transforming constructs. And, recently, a considerable body of independent research is also examining this area of research in the context of aerial robots with high configurational transformational capability, e.g., Ref. 17.



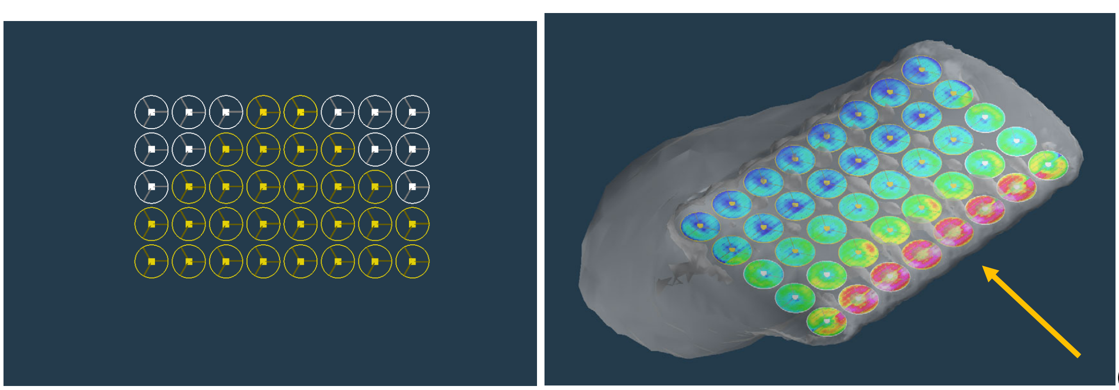


(c)

(d)

**Figure 19. From matrix to array (edgewise forward flight, 20ft/s): (a) original square matrix layout, (b) sweeping of one set of edges, (c) sweeping of second set of edges, and (d) final flying wing/linear-array layout**

Figure 20 is an alternate two-dimensional (mid-flight) transforming construct. The mechanical linkages tying together individual flying elements could have actuated hinges to allow for the relative movement of the elements in the original two-dimensional layout to reposition (and, if need be, partially separate) themselves to form a second construct layout, even potentially inflight.



(a)

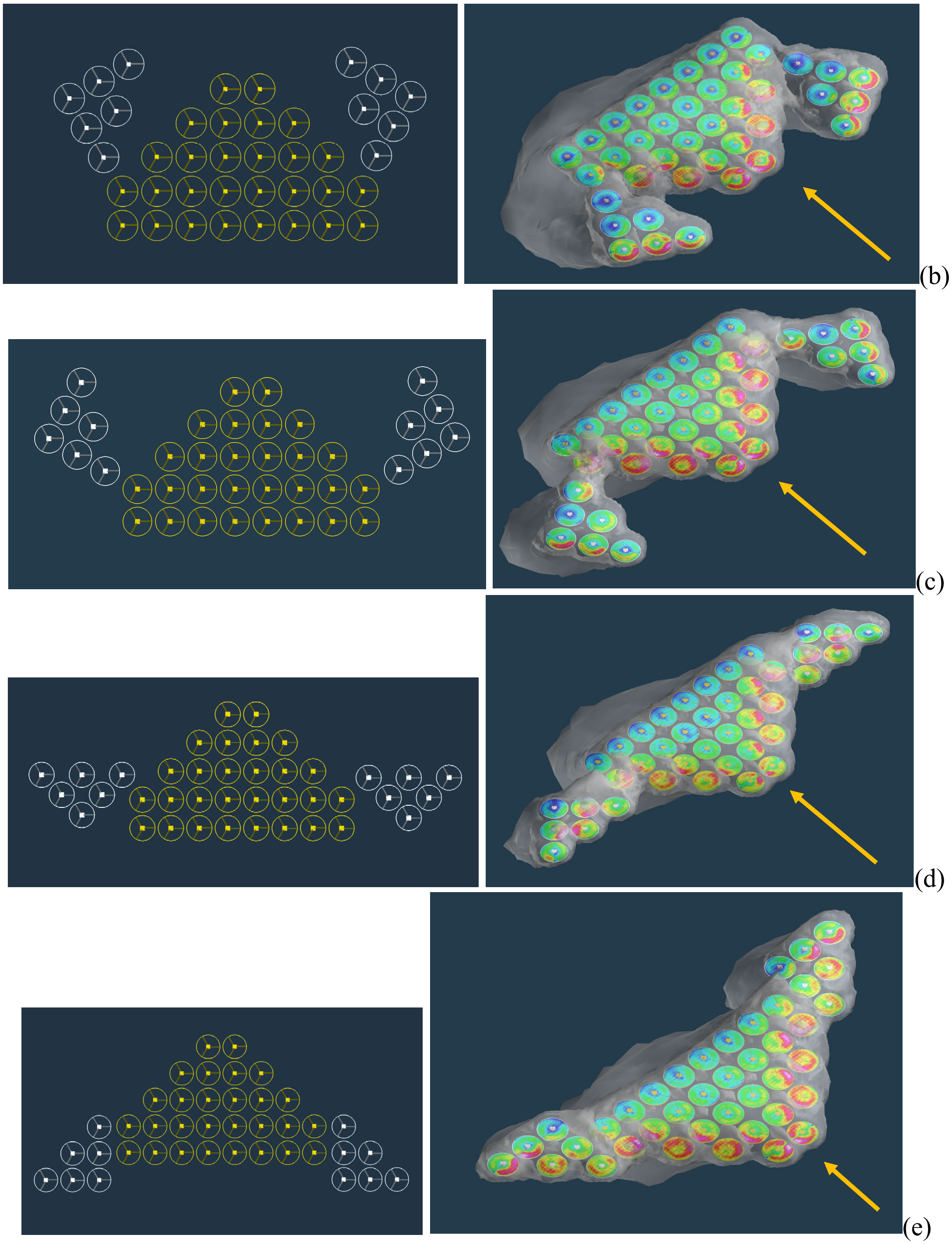



**Figure 20. Two-dimensional Sierpinski triangles pivoting from square matrix to delta shape: (a) original square matrix layout, (b) initial pivot of two sections of construct, (c) further pivoting of sections, (d) pivot and alignment to rear of assembly, and (e) final flying wedge type layout**

### Three-Dimensional Assemblies

The best 3-D construct assemblies might be origami-like, i.e. formed from ‘folded’ two-dimensional assemblies. Alternatively, Lego$^{TM}$ -like structures might also present viable approaches to the assembly of UFM constructs. And, finally, tethered and mechanically linked (through truss-structures) might be a third approach to assembly of constructs.

#### *Stationary*

Figure 21 is a simple geometric form, notionally a cone-like tower or ‘stele’. From a static structural perspective, such a geometric form might be an ideal form for a temporary stationary structure formed out of elements, prior to their disassembly and individual flight.

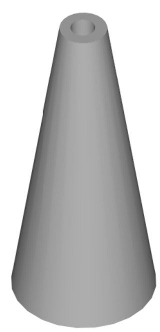
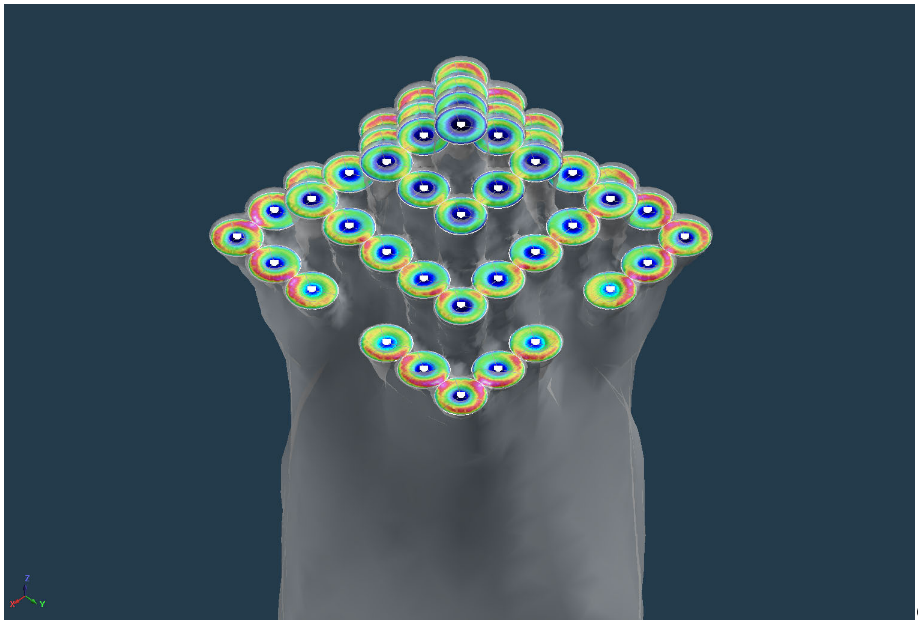


**Figure 21. Towers or Stele**

Figure 22a-b is a simple representational (rotors only) illustration of a UFM construct forming a tower or stele. It might be imagined that such UFM-formed stele might be used as perimeter stations to protect high-value installations. Further, the installation comes under external threat, the UFMC stele construct could disassemble into a swarm of flying UFME to counter the threat.

Figure 22a-b presents RotCFD results for a tower or stele of (rotors-only) notional UFM elements forming a construct.


(a)

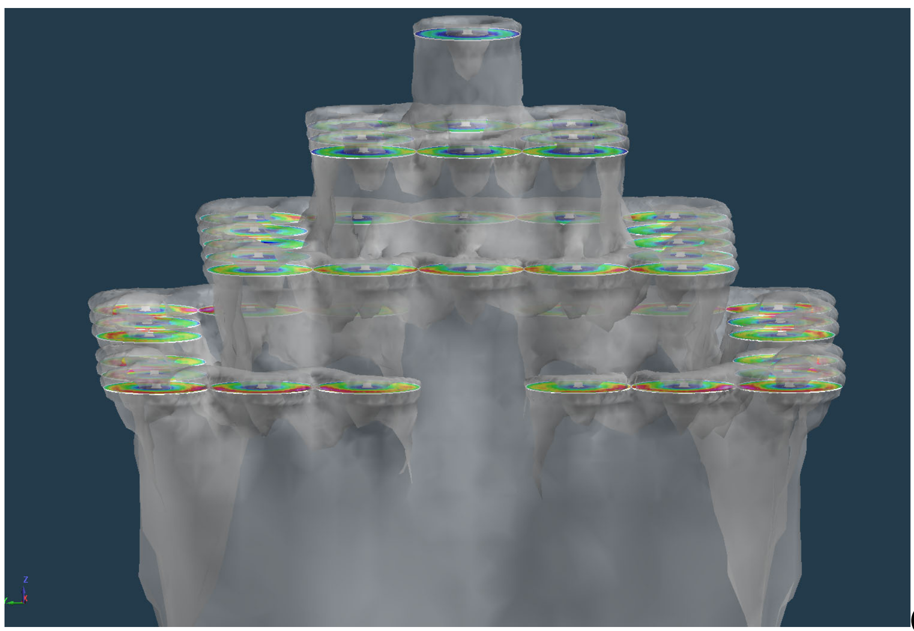
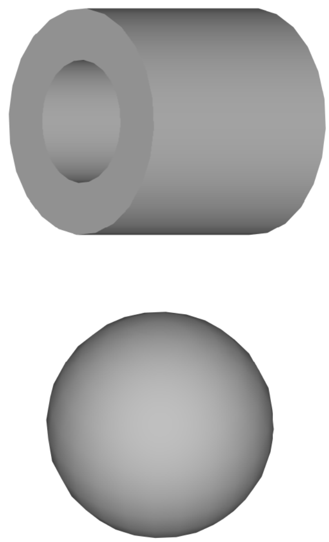

(b)

**Figure 22. Mid-fidelity CFD (hover) of a UFMC tower: (a) isometric view and (b) custom near-side-view**

*Ambulatory*

Structures or simple machines that are also UFM constructs are considered from the perspective that the construct exhibits some level of ambulatory motion capability, either flying or nonflying, when assembled. Figure 23 illustrates two simple three-dimensional shapes that could possibly be formed by constructs. Figure 23a-b presents cylindrical and spherical shapes that could be formed by UFMC that could allow possible flight and rolling ground mobility (use timed multirotor differential thrust to enable that locomotion).



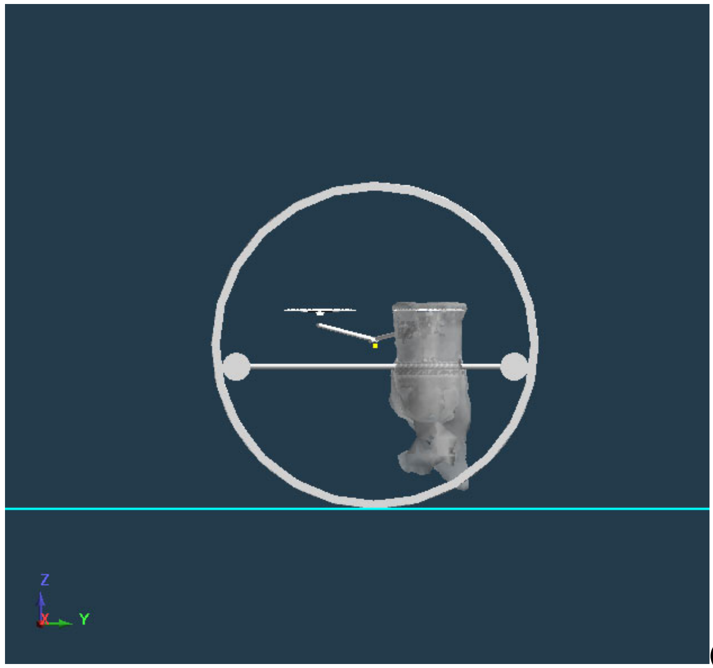
(a)

(b)

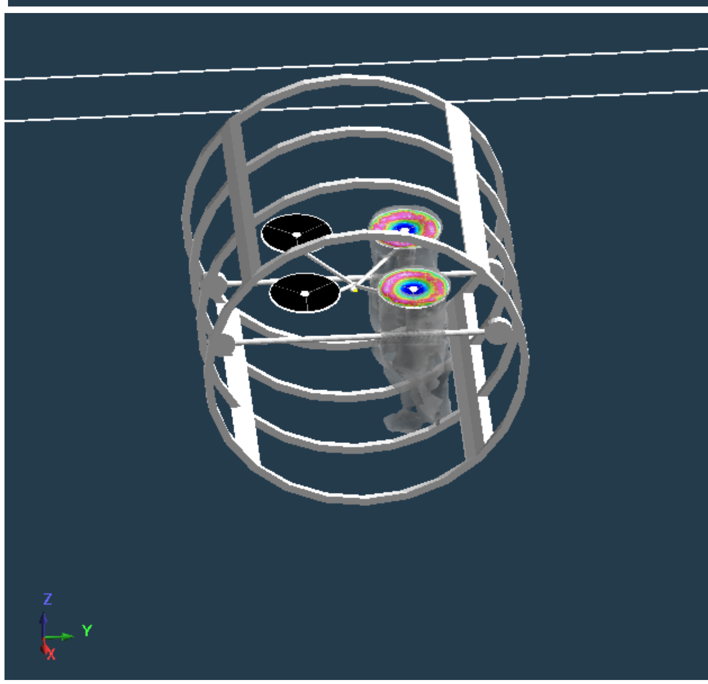
**Figure 23. Rolling: (a) cylinder and (b) spheroidal**

First, consider a roller UFME as illustrated in Fig. 24. Only one pair of quadrotor's rotors are acting at given time (in a thrust pulse or thrust ramp-up and ramp-down) to cause the frame of the element to roll forward (or backward if the other pair were operated). Steering of the element could be implemented by differential thrust between the two rotors of a given pair.

Even at its simplest level, a single roller element, rotor-actuated ground mobility capability is challenging from a controls and dynamics perspective. From a flight and ground mobility management perspective, the UFMC problem is even more challenging. Such challenges, though, are what inspire engineers. Hybrid air/ground mobility vehicles/systems promise a range of potential application domains to explore, irrespective of whether they embody universal flying machine attributes. Application domains best suited for air/ground locomotion are longer, sustained missions where the speed/range of flight can be satisfactory traded-off against the slower but more efficient ground locomotion. Further, hybrid air/ground mobility vehicles/systems must be underpinned by missions that perform significant tasks while on the ground. Correspondingly, those application domains best suited for UFM are those that require vehicles/systems to perform sustained distributed tasks, functions, or services.



(a)



(b)

**Figure 24. A roller UFM element; only one pair of the quadrotor rotors are thrusting at a given moment to apply a torque to the roller frame and, therefore, result in a rolling motion of the element: (a) side view and (b) isometric view**

A spheroidal construct is shown in Fig. 25a-b using triangular UFM elements with a triple set of coaxial rotors nested within the triangular fixed-frame. These triangular elements can be joined (potentially hinged joints) at their edges and vertices with other triangular elements.

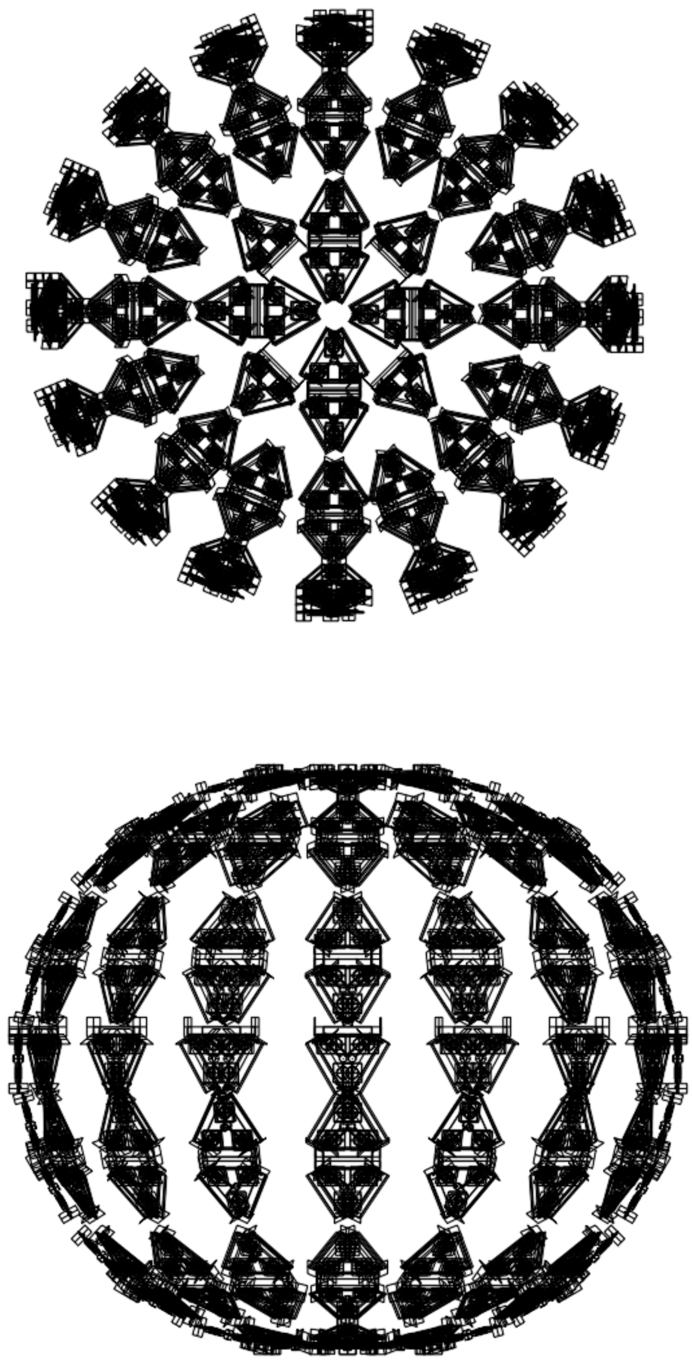
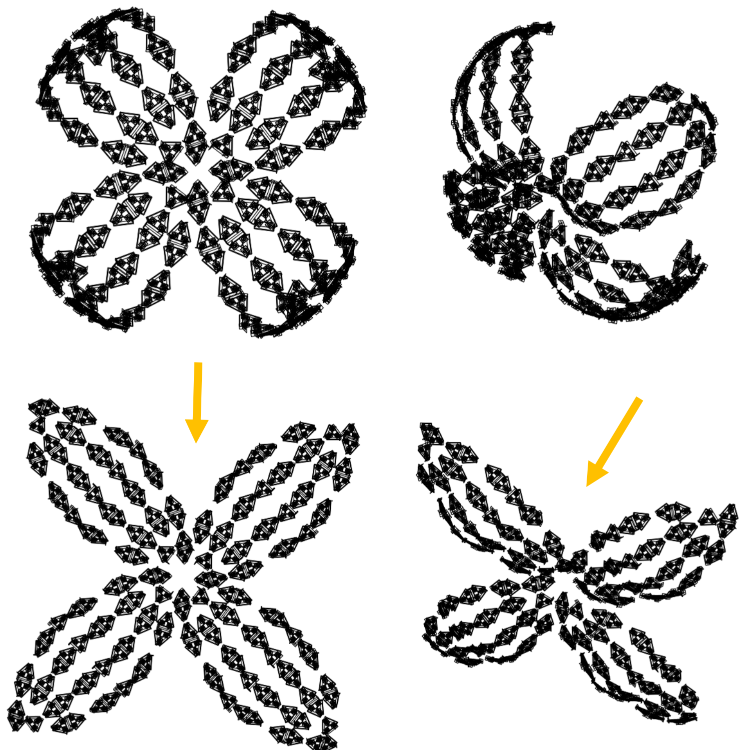


**Figure 25. Rolling and bouncing (using tri-coaxial rotors – aka hexacopter – and three lifting surfaces for actuation for movement)**

The Fig. 25a-b spheroidal construct can be invariant in shape when undergoing ground locomotion or during flight. However, in addition to disassembly from construct to element there is another interesting in-between state in which the construct changes its shape or morphs/transforms in flight or on the ground. This ability to morph or transform will be discussed further in the next section.

***Flying***

Several different 3-D assemblies suggest themselves for free-flying UFM constructs, i.e. UFMC. Among those 3-D assemblies are ring- or tube-like structures. The rotors embedded in the individual UFM elements, i.e. UFME, would by necessity have to have one- to two-DOF (degrees-of-freedom) as to their tilt angles. These UFME variable rotor(s) tilt (mechanisms) would allow certain sectors of the ring- or tube-structures comprising the construct geometric configuration to be separated into 'lifting' and 'thrusting' (i.e. propulsors) rotors.



(a)

(b)

**Figure 26. Previously shown "roller/bouncing' sphere unfolding (like an orange peel) to form a pseudo-two-dimensional flying array: (a) sphere unfolded partially to forty-five-degree angle and (b) sphere unfolding nearly completely act as a flying array**

## A Matter of Scale

It is perhaps hard to currently envision dozens, let alone hundreds or even thousands, of individual UFM elements contributing to a single UFM construct, but that might be the goal for certain large-scale missions and application domains. Such constructs could physically be very large or, if the individual UFME could be sufficiently miniaturized to keep the UFMC modest in size. This matter of scale is therefore contingent upon advances in technology as well as novel application domains being explored. Perhaps the general concept of constructs can be considered the ultimate bioinspiration as applied to robotics, for UFMC relative to a multitude of UFME can be thought of analogously as an organic multicellular body or organ relative to the individual cells.

## General Strategies of (Multi-)Configurational Design

### General Strategies for Control

Major (novel/unique) states for UFME and UFMC control are listed in Table 3. This table defines a parameter, the level of constructs control authority (LOCCA), that aides in conceptualizing the novel states and strategies of control available for UFM.

**Table 3. Levels of Construct Control Authority (LOCCA)**

| LOCCA | Description |
|---|---|
| | |
| 1 | Stationary and immutable (except for construct disassembly and/or assembly at the beginning and/or end of the construct formation); each element of the construct is treated control-wise as a semi-independent system; even when interlocked/connected/assembled into a construct, the operation of the UFMC is more like a loosely coordinated swarm of free-flyers |
| 2 | Nonstationary (one mode of mobility as a construct) but immutable in construct form/configuration; small clusters of elements can be treated uniformly, in that the same control inputs can be applied to all elements in |

| | |
|---|---|
| | each cluster; the sum of all clusters plus the remaining independent elements must constitute the whole of the complete construct |
| 3 | Nonstationary (construct is at least capable of flight) but immutable; control is highly coordinated and distributed throughout the construct |
| 4 | Nonstationary with multi-modal mobility (hybrid air/ground mobility or some other two or more modes of mobility) but immutable in form; when in flight, control is highly coordinated and distributed throughout the construct; however, when other mobility modalities are enabled, then the cluster control approach noted above must be employed; further, as it is likely that large ranges of construct attitude angles and rates will result while operating in non-fight modalities, then the construct orientation and rates will likely highly inform time-dependent control inputs |
| 5 | Nonstationary with multi-modal mobility and capability of morphing or transforming form and function (transformation can happen on the ground while construct is stationary); in addition to the control authority insights noted in LOCCA=4 description, each transformed configuration state of the construct will likely have its own set of distinct control laws |
| 6 | Nonstationary with multi-modal mobility and capability of morphing or transforming form and function (transformation must have mid-flight); transformation in mid-flight will be further challenging in that satisfactory flight characteristics will have to be maintained while even in intermediate states of transformation; further such transformation might not be considered to have quasi-steady, but rather dynamic, aerodynamics to consider while subjected to flight control inputs. |
| | |

Clusters are just smaller, simpler constructs that when assembled with other clusters and elements form larger constructs. Clusters are introduced as a supplemental concept to better illuminate flight control aspects of constructs through various stages of multimodal mobility operation as well as possible morphing or transformation stages of construct reconfiguration. The greater the complexity of the construct and its operation the greater the likelihood of nonlinear rotor-on-rotor, rotor-on-element, and cumulative rotor-on-construct interactional aerodynamics will begin to manifest themselves.

The field of study of universal flying machines inherently adopts the adage "the whole is greater than the sum of the parts".[1] This is perhaps no truer when conceptualizing UFM constructs as simple (but large-scale) machines. The machines that could be formed from UFM constructs range from simple Archimedean-type machines to complex multiple degrees of freedom robotic systems could potentially be within the field of study for universal flying machines. In the case of the emulation, or embodiment, of machines using several rotors, or thrusters, as a part of a UFM construct instead of servomotors or linear

[1] The origin of this saying is attributed to Aristotle in his 'Metaphysics'.

electromechanical actuators used in a specialized piece of equipment represents unique challenges and opportunities.

It is when UFM constructs begin to encompass attributes of machines that there results in an intersection between the two fields of study: universal flying machines and 'rotorcraft as robots', e.g., Refs. 11-12. Table 4 begins to define levels of machine construct control authority that might describe the attributes of UFMC 'machines.'

**Table 4. Levels of 'Machine' Construct Control Authority (LOMCCA)**

| LOMCAA | |
|---|---|
| | |
| 1 | Simple (Archimedean-type) machine; Rotors/thrusters together provide only one degree-of-freedom operation; additionally, there is minimal rotor-on-rotor, rotor-on-element, or rotor-on-construct interactional aerodynamics throughout all phases of operation |
| 2 | Two degrees of freedom |
| 3 | Three degrees of freedom |
| 4 | Multi (higher than three) degrees of freedom |
| 5 | Complex machine |
| | |

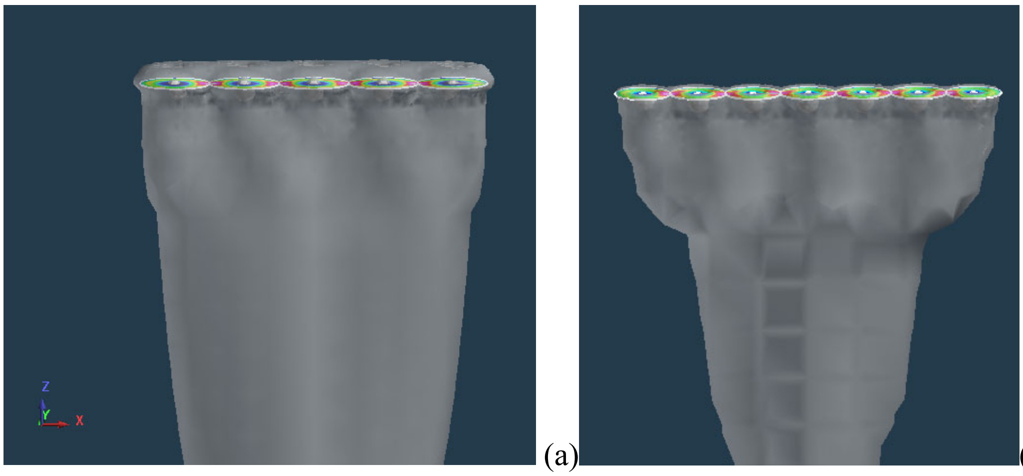
Though some limited mid-fidelity CFD results have been sprinkled throughout the report so far, a more detailed, but still preliminary, study of the rotor-on-rotor aerodynamic interactions of UFM constructs of various forms will now be presented and discussed.

## Some Limited Analysis Results

The key aerodynamic limitation of arrays and three-dimensional assemblies of VTOL UFM elements being intertwined/integrated into a UFM construct is that there could potentially be significant rotor-on-rotor and body-on-rotor aerodynamic/wake interference effects. These rotor-on-rotor and body-on-rotor interference effects can be judiciously moderated to some extent by careful consideration of rotor-to-rotor vertical and horizontal staggering/spacing in an aggregate construct, under nominal flight conditions. Mid-fidelity CFD and other analysis tools currently exist, though, that can be used to provide for some design guidance of UFM constructs (in addition to being equally applicable to UFM elements).

### *Horizontal Spacing*

Figure 27a-b are UFM constructs that are five and seven elements attached respectively in a horizontal linear array while in hover out of ground effect conditions.



(a) (b)

**Figure 27. Mid-fidelity, virtual disk, CFD hover out of ground effect (HOGE) predictions: (a) five element linear array and (b) seven element linear array (rotor-to-rotor spacing for both cases is 2R)**

Figure 28a-b and Fig. 29a-b examine the influence of rotor-to-rotor spacing on five and seven element horizontal linear arrays in hover out of ground effect. Figure 28a-b and Fig. 29a-b are distributions of thrust (normalized by isolated rotor thrust) and power loading (P/T) among the individual rotor elements along the span of the linear arrays. Figure 30a-f are series of mid-fidelity, virtual disk, CFD predictions of the rotor wakes and rotor differential pressure distributions across the rotors for the construct horizontal linear arrays.

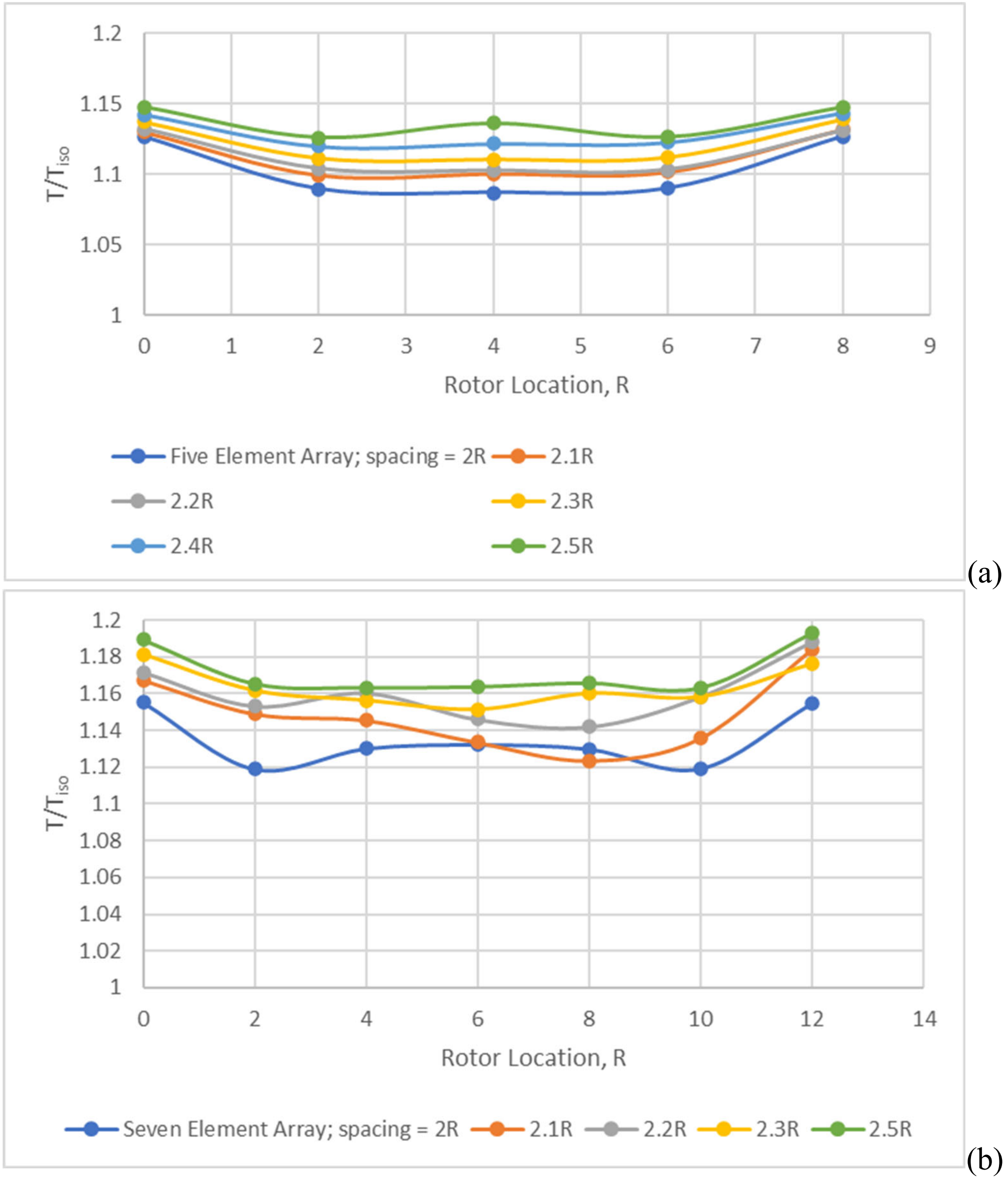
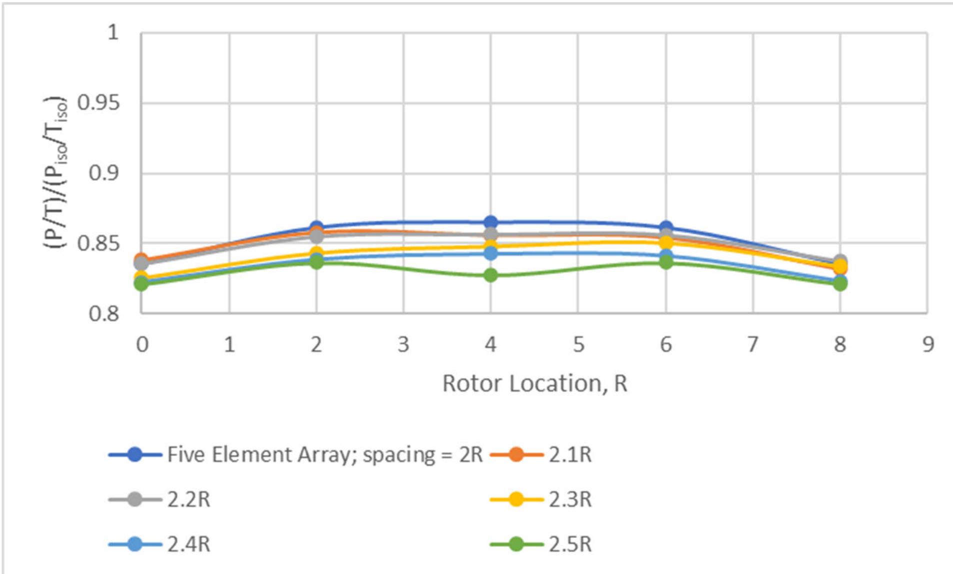
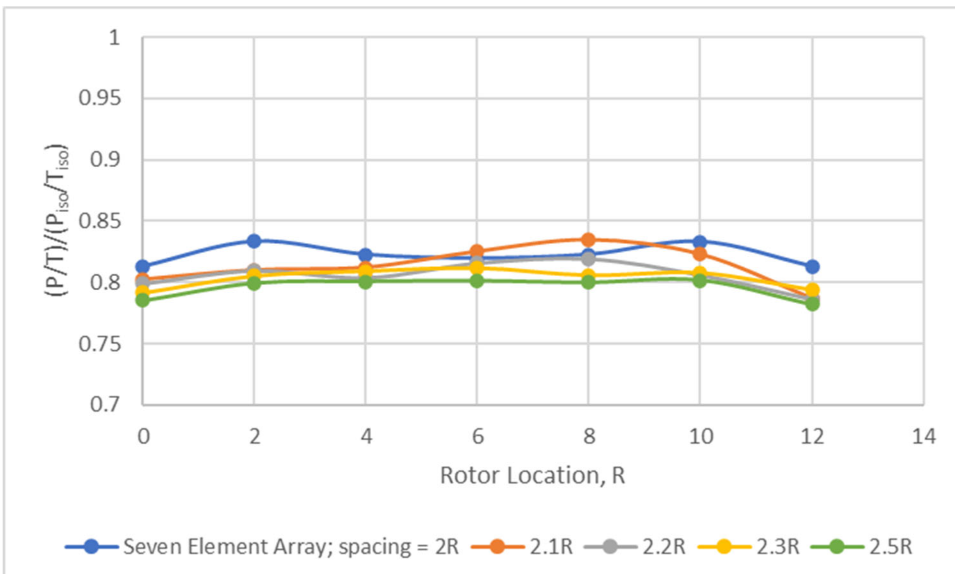



**Figure 28. Normalized thrust trends for horizontal linear arrays in HOGE: (a) five element array and (b) seven element array**



(a)



(b)

**Figure 29. Normalized power loading trends for horizontal linear arrays in HOGE: (a) five element array and (b) seven element array**

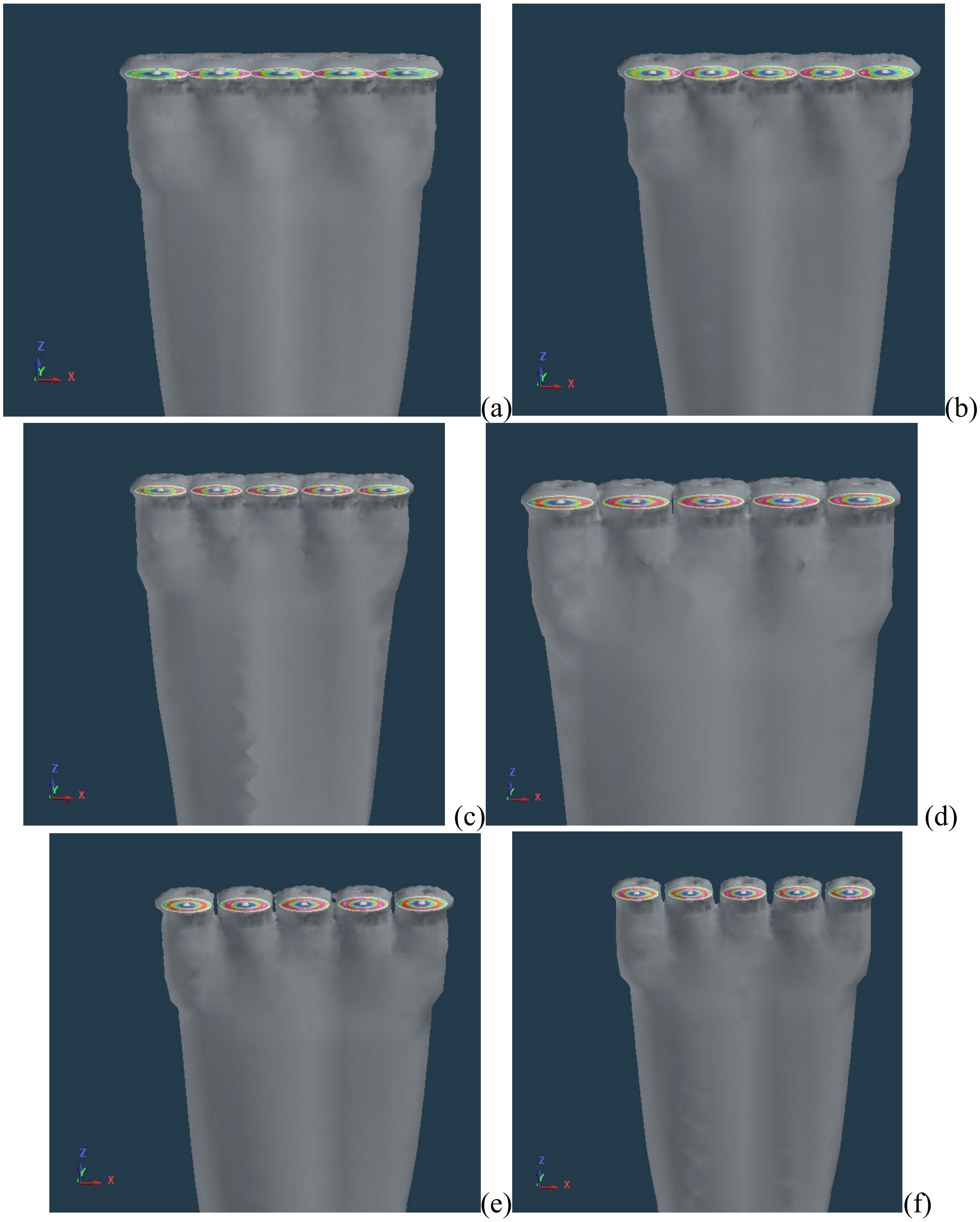
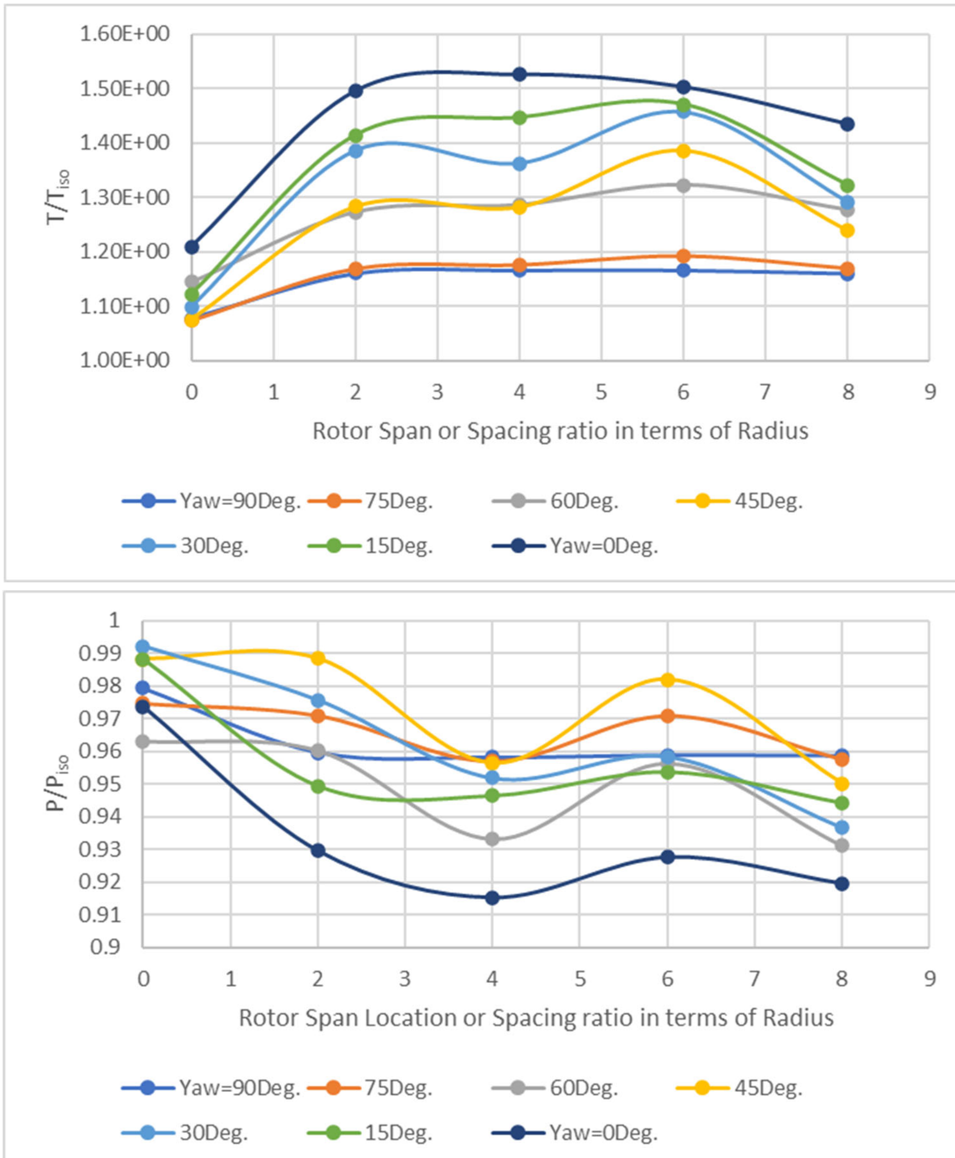



**Figure 30. Mid-fidelity, virtual disk, CFD HOGE predictions (five elements): (a) rotor-to-rotor spacing of 2R, (b) spacing of 2.1R, (c) spacing of 2.2R, (d) 2.3R, (e) 2.4R, and (f) spacing of 2.5R**

Figure 31a-b considers edgewise forward flight for a construct composed of a horizontal linear array of elements (with single rotors) with a rotor-to-rotor spacing of 2R. Figure 31a-b presents the normalized (with respect to isolated rotor thrust) thrust trends, as well as the power loading (P/T) trend, as a function of spanwise distribution for various yaw angles of the array with respect to the freestream velocity.




(a)

(b)

**Figure 31. Normalized thrust ($T/T_{iso}$) and power ($P/P_{iso}$) trends for horizontal linear arrays in HOGE: (a) thrust and (b) power as a function of rotor span or spacing location**

It is conjectured that the reason why the Fig. 31 distribution for the yaw angle of zero degrees is not symmetrical (thrust at rotor #1 is not the same as the thrust of rotor #5) is because the total number of rotors in the linear array is not an even number. The other curves exhibiting spanwise asymmetry is because the rotor distribution shifts from a lateral distribution to a longitudinal distribution with increasing array yaw angles.

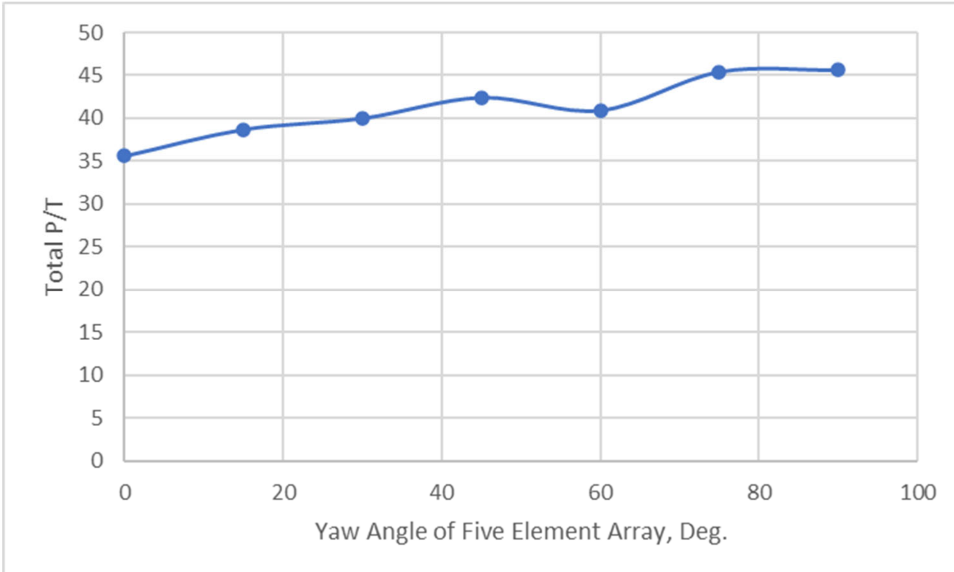
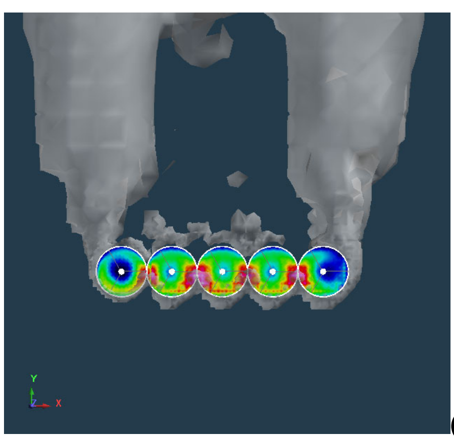
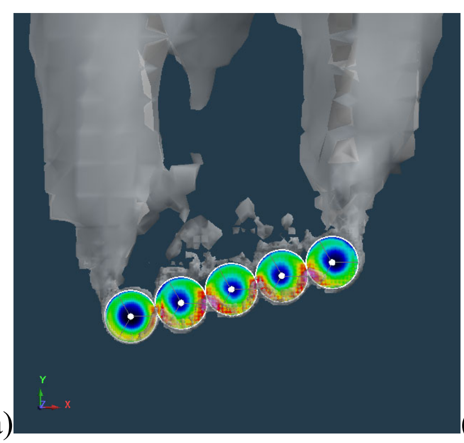



**Figure 32. Average P/T ratio as a function of yaw angle for five rotor element array for advance ratio of 0.033 (constant collective for all rotors of 10Deg. and zero pitch angle)**

Figure 33a-g presents illustrative edgewise forward flight CFD results for the aggregate rotor wakes (nondimensional Q-criterion to highlight the vorticity in the array 'super vortices') and the rotor differential pressures across the rotor disk for the horizontal linear array at different yaw angles. The rotor/linear-array pitch attitude is zero degrees; the rotor tip speeds are 600ft/s and the forward velocity is 20ft/s for a low advance ratio of 0.03; all collectives are uniformly 10Deg. and all rotors have untwisted blades with NACA0012 airfoils.


(a)


(b)

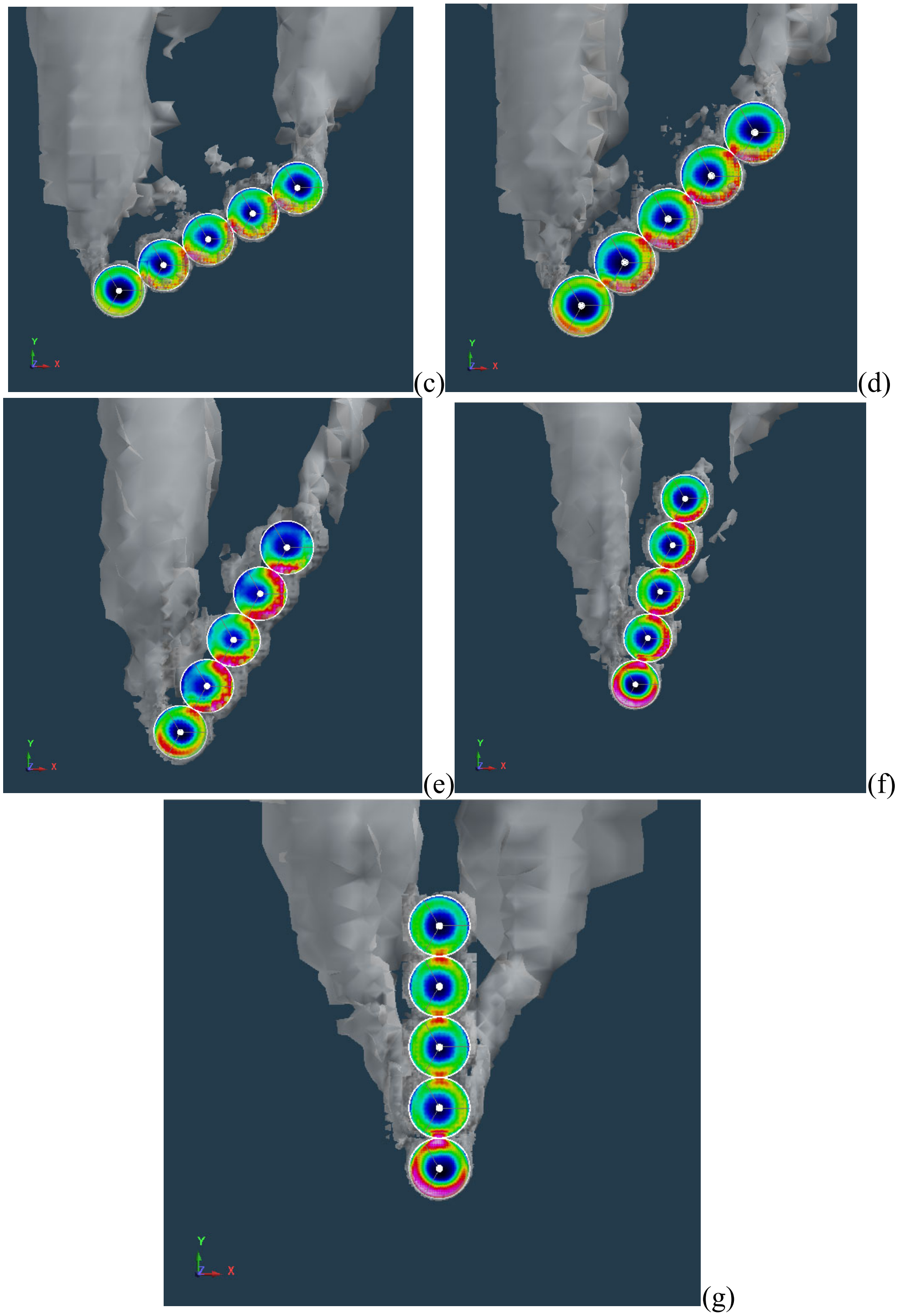



**Figure 33. Mid-fidelity, virtual disk, CFD HOGE predictions (five elements at a rotor-to-rotor spacing of 2R; all isosurfaces are at a uniform nondim. Q-criterion value): (a) yaw angle = 0Deg., (b) yaw angle = 15Deg., (c) yaw angle = 30Deg., (d) 45Deg., (e) 60Deg., (f) 75Deg., (g) 90Deg.**

Figure 34 illustrates the hover results (isosurfaces of rotor wake velocity magnitude and color contour of rotor differential pressure across the rotor disks) for a single-layer, five-by-five matrix of rotors (for a rotor-to-rotor spacing of 2R). Figure 35 are the partial hover out of ground effect thrust coefficient results of this single-layer, five-by-five matrix of rotors (-only) for range of rotor-to-rotor horizontal spacings.

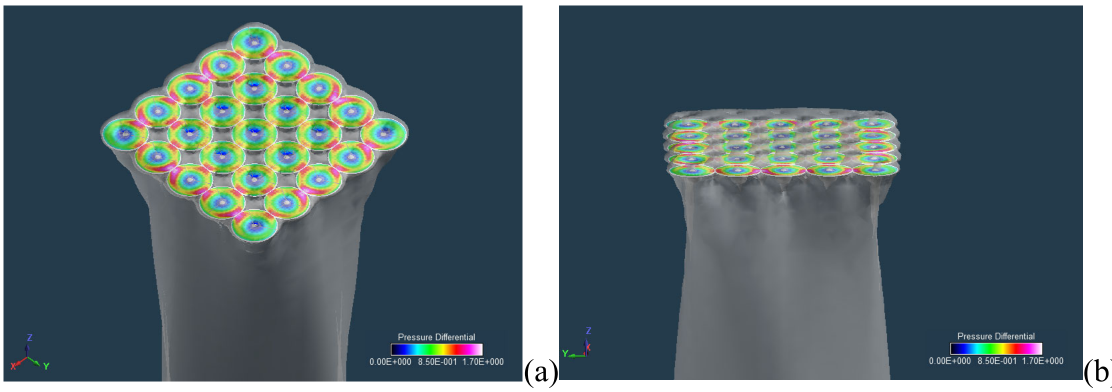



**Figure 34. Hover CFD results for a single-layer, five-by-matrix of rotors-only for a horizontal spacing of 2R: (a) isometric view and (b) side view**

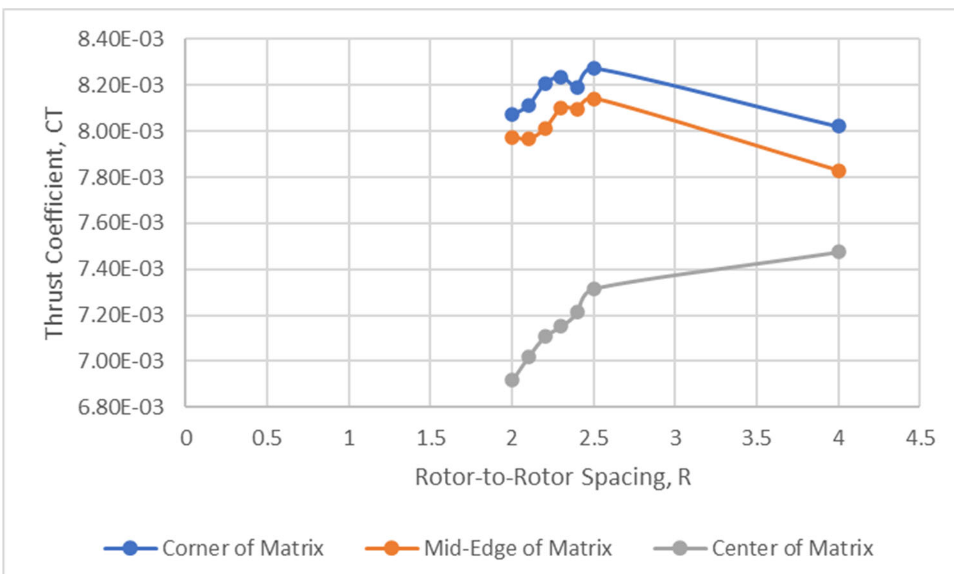
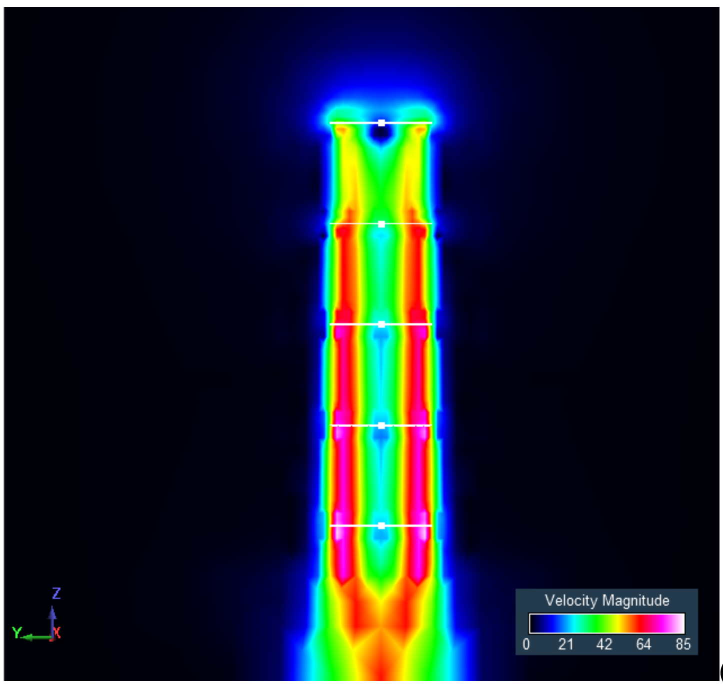


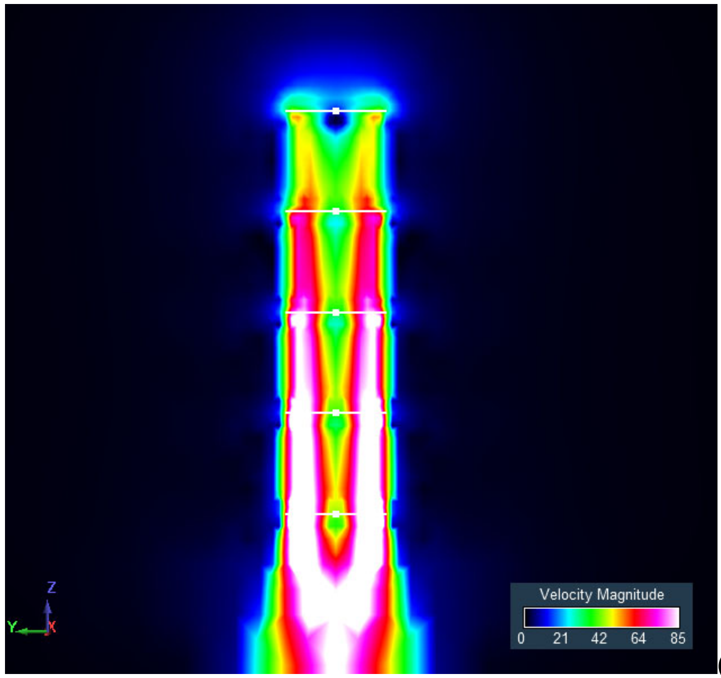

**Figure 35. Thrust coefficient versus rotor-to-rotor spacing of a single-layer, five-by-five matrix of rotors.**

### *Vertical Spacing*

Figure 36a-b is vertical linear array of rotors aligned collectively with each other's rotational axes. Figure 36a are the flow field (contours of rotor wake velocity magnitude) results for all rotors having the same fixed collective. Figure 36b is the flow prediction where all rotors are trimmed (by means of rotor pitch angle collective) to approximately have the same thrust coefficient (CT=0.0079). It is an open question as to how many rotors can be vertically 'stacked' above each other before it becomes ineffective to increase the subsequent downstream rotors' collective angles to compensate for the additive increase in rotor inflow from the upstream rotors.



(a)



(b)

**Figure 36. Mid-fidelity, virtual disk, CFD of construct with a vertical linear array of rotors (a) uniform collective for all rotors and (b) all rotor collectives are trimmed to a uniform thrust level**

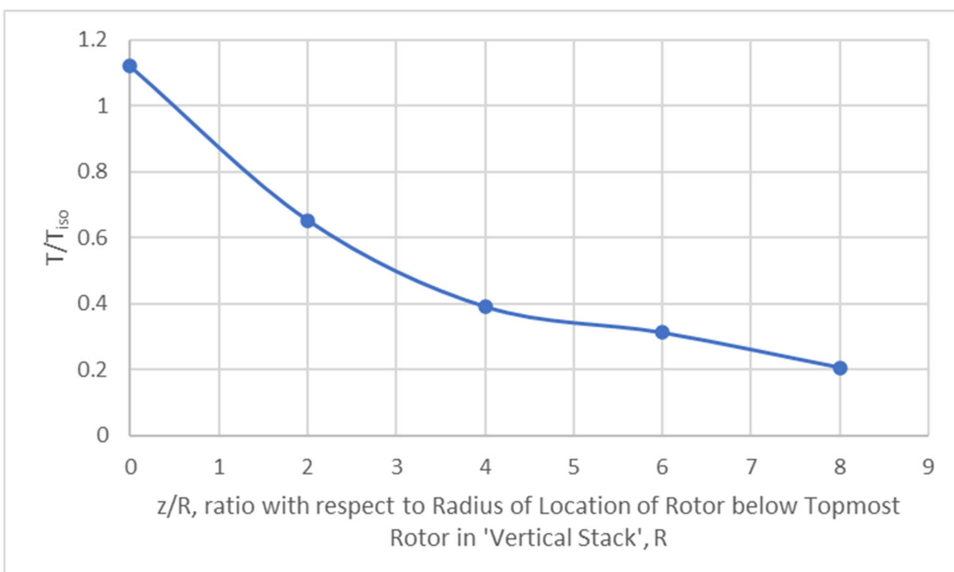



**Figure 37. Thrust ($T/T_{iso}$) distribution as a function of vertical location (z/R) in rotor element 'stack'; increasing z/R is equivalent to being lower in the stack (and therefore subject to greater induced velocities from the rotors above it)**

Figure 38 clearly shows that a rotor being lower in a vertical stack of other rotors suffers from not only diminishing thrust capacity (for fixed, uniform collective for all rotors) but also substantially increased power loading (P/T) relative to the power loading with respect to an isolated rotor (except for the topmost rotor in the vertical stack).

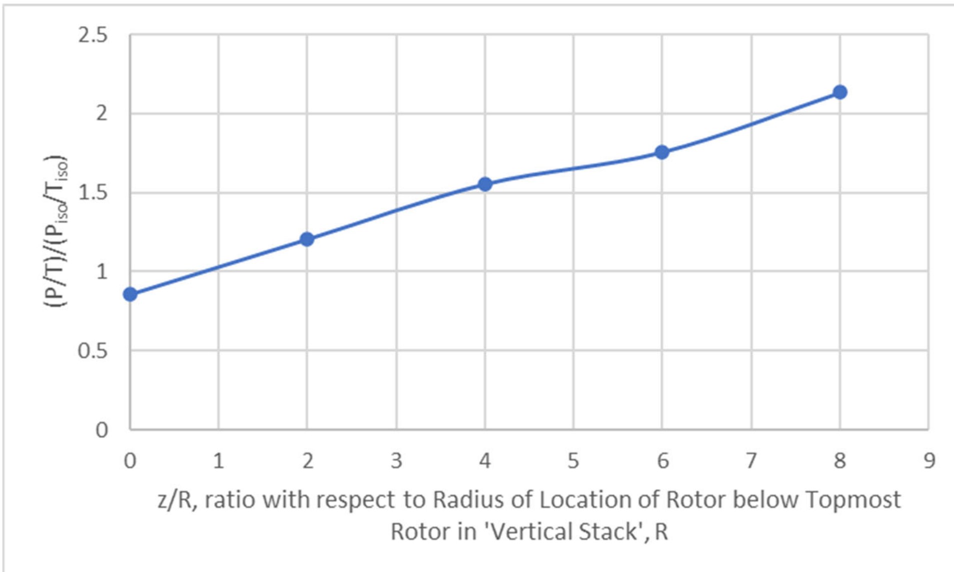



**Figure 38. Power loading (P/T) distribution as a function of vertical location (z/R) in rotor element 'stack'; increasing z/R is equivalent to being lower in the stack (and therefore subject to greater induced velocities from the rotors above it)**

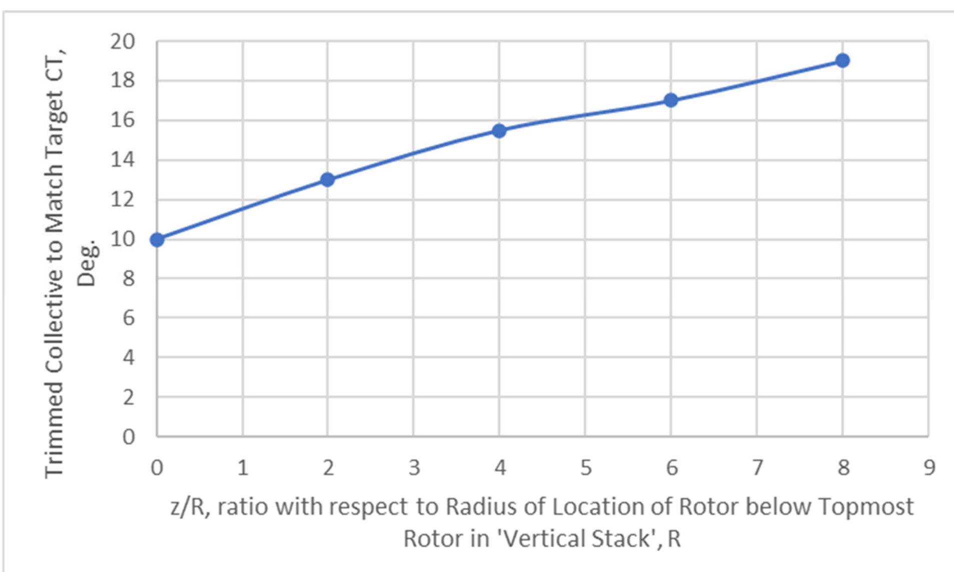
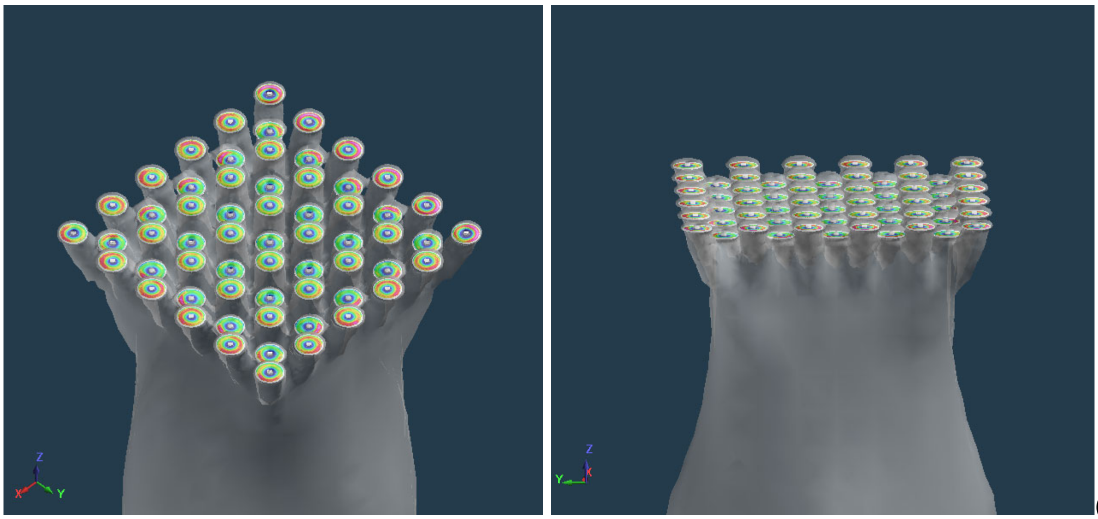
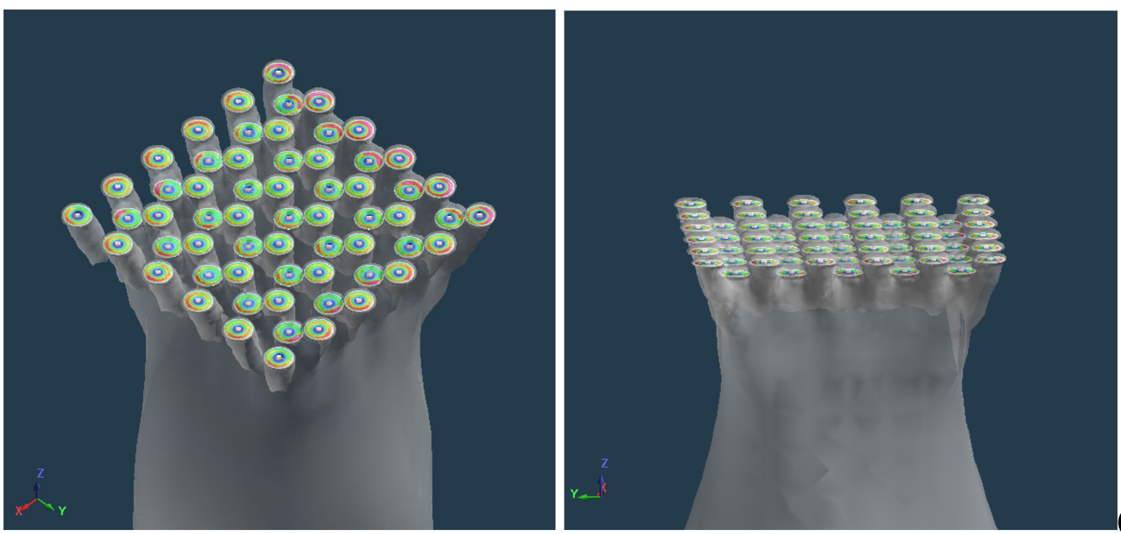



**Figure 39. Rotor collective trimming (target thrust coefficient, CT=0.0079) to maintain approximately the same thrust for all rotors as a function of vertical location (z/R) in the rotor element 'stack'**

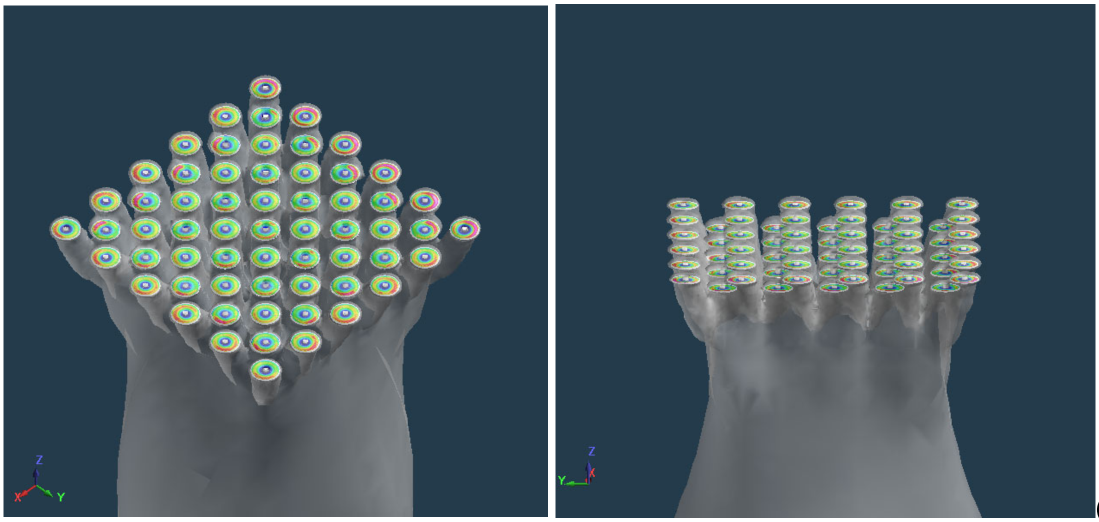
Figure 40a-c presents a two-layer vertical stack of a five-by-five (upper layer) and a six-by-six square (lower layer) matrices of rotors in HOGE.




(a)




(b)




(c)

**Figure 40. Influence of relative horizontal shift: (a) zero-offset, (b) lateral offset between two vertical layers, and (c) diagonal offset between two vertical layers**

Figure 41 presents the total thrust coefficient results of all rotors in the two-layer, five-by-five and six-by-six matrices. The differences in thrust coefficients between zero offset (most upper rotors are directly above the lower rotors) and small lateral or diagonal offsets/shifts are small, especially as compared to the much larger differences in general between the upper and lower layers of rotors.

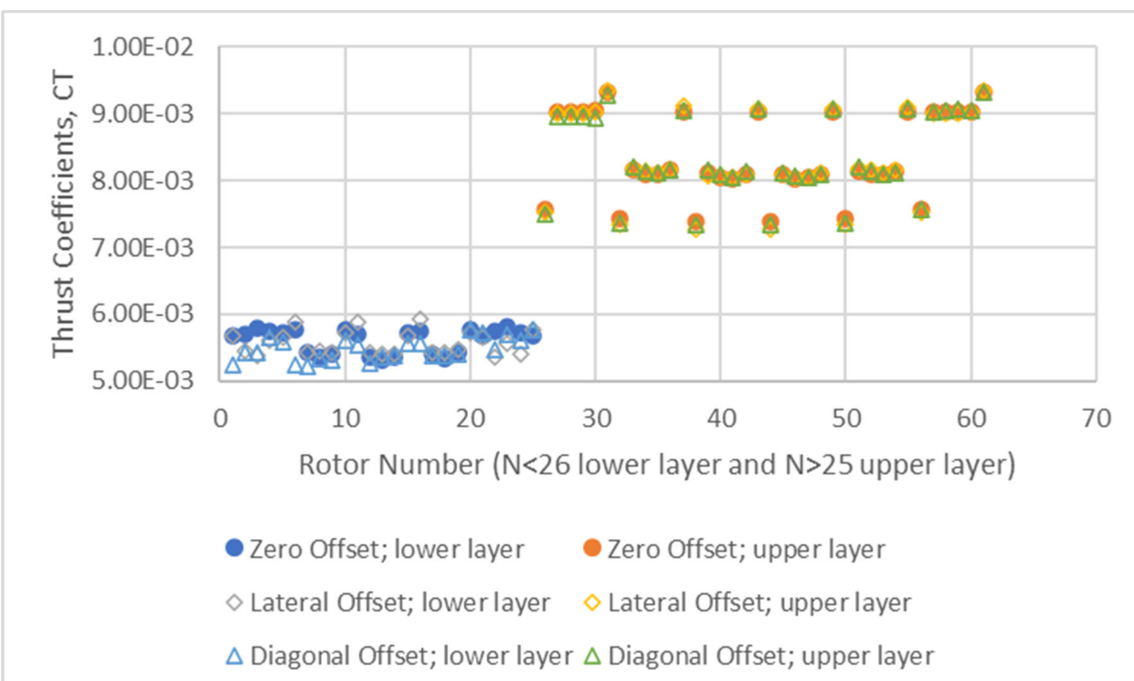



**Figure 41. Rotor thrust coefficient distributions for the two-layer five-by-five and six-by-six matrices**

## Some General Thoughts Regarding Enabling Reversible Assembly/Disassembly of Constructs

As noted before, it is likely far easier to disassemble than assemble a UFM construct from elements. First generation UFM constructs will, therefore, likely focus on designs and missions that focus on irreversible disassembly during some portion of their mission. And certainly, the weight/mass constraints of flight dictate that not too much vehicle weight fraction can be devoted to onboard assembly/disassembly hardware/mechanisms. For example, magnets have been proposed for similar assembly and/or disassembly mechanisms for elements to form constructs for toys and for ground mobile robots. However, magnets and ferromagnetic surfaces to which they might magnetically attach too are comparatively very heavy – or if electromagnets were employed would be very electric power intensive – and thereby might make them unsuitable for aerial vehicle elements being assemble/disassembled into constructs.

## General Concepts Applicable to Any Three-Dimensional Mobility Element/Construct and Operating Environments

The UFME and UFMC concept does not need to be restricted to rotors, fans, or propellers. Further, the UFM concept does not even need to be restricted to "flying" or operation in air. For example, in discussion in the later sections of this report, a possible application of the UFM concept will be discussed for space applications/capabilities.

Several example cases of three-dimensional constructs will now be discussed. The list below is not, however, exhaustive or do the missions noted below reflect the most critical applications to which UFM might ultimately be applied to. However, it is hoped that this list of three-dimensional mobility concepts and their possible missions might prove to be inspirational as to a community of aerospace innovators. Further, some of the challenges note below will also help inspire new technologies and new implementation approaches for UFM and 'rotorcraft as robots.'

### *Example Case #1: "Rolling" Ground Mobility and Aerial Flight*

The first example test case presented is for a UFM construct that embodies aerial flight with the ability to perform "rolling" ground mobility. The specific construct configuration is of a cylindrical three-dimensional assembly, Fig. 42.

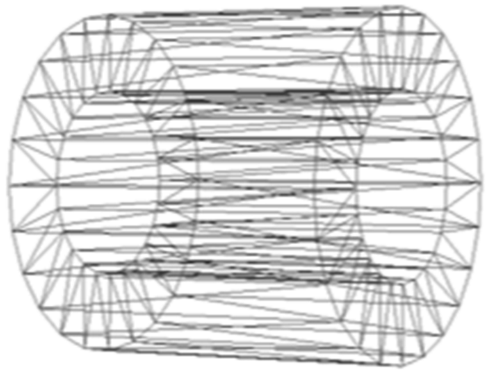
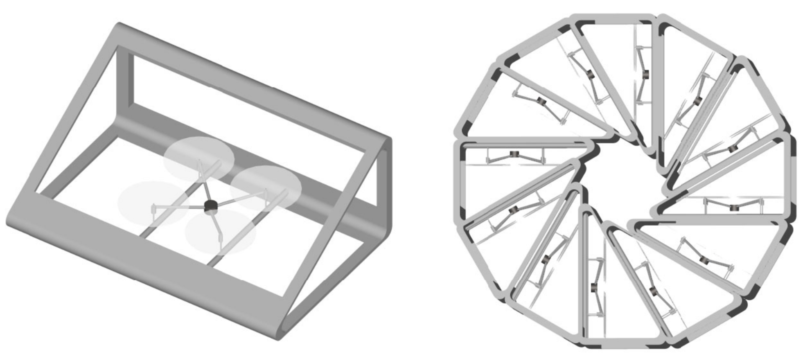
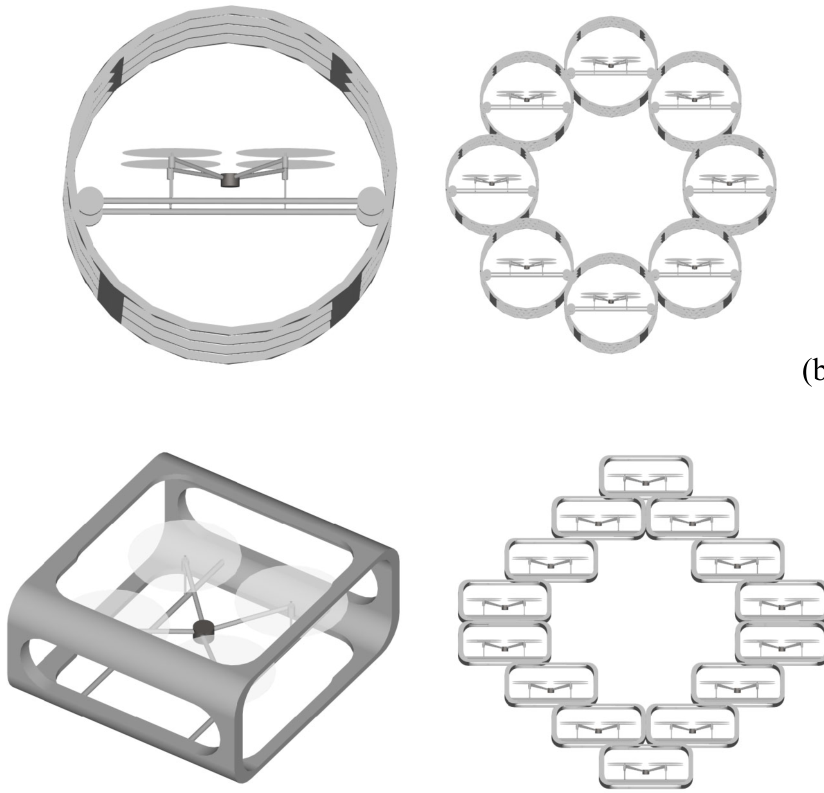


**Figure 42. "Rolling" Ground Mobility**

The UFM elements that can be incorporated into such a cylindrical assembly can be of several different types and intrinsic capabilities. Figure 43 illustrates some of the various UFM element types that could be used for this cylindrical assembly construct. These elements range from those types of designs optimized for "rolling" ground mobility to those elements that could be optimized for efficient hovering and forward-flight. A few notional "in-between" element types are also included in Fig. 43.



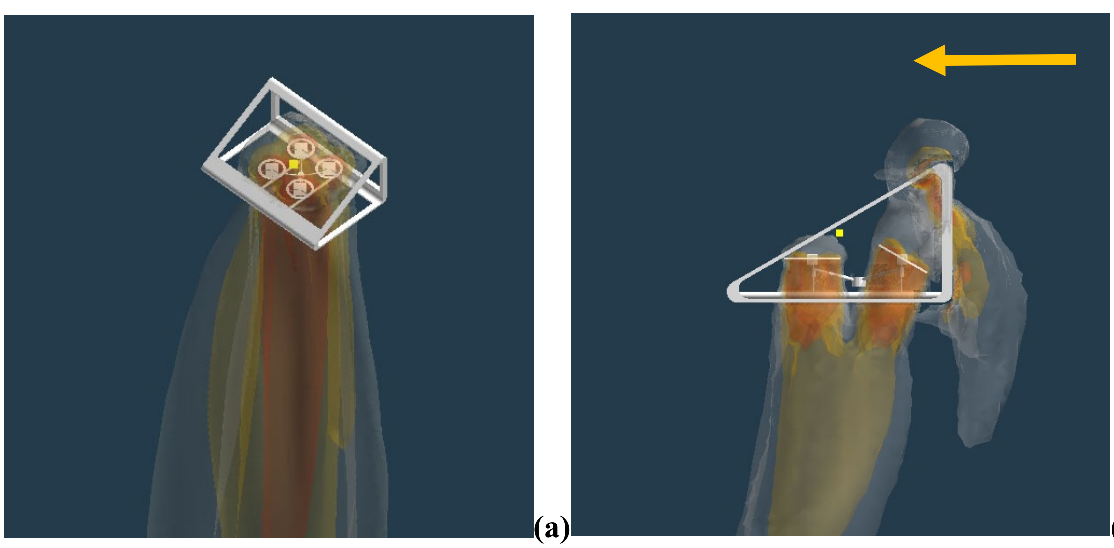
(a)



(b)

(c)

**Figure 43. "Rolling" Ground Mobility and Aerial Flight; notional elemental geometries: (a) optimized for "rolling" ground motion, (b) alternate approach with individual 'roller' elements, and (c) second alternate approach with individual 'non-round' elements**

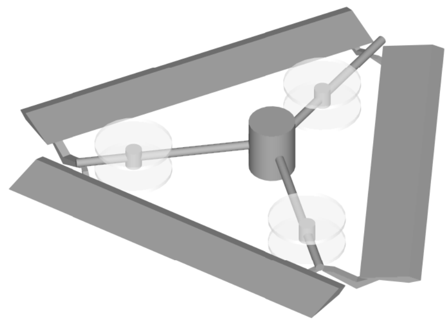


(a) (b)

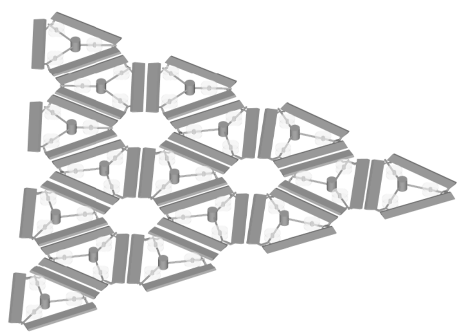
**Figure 44. CFD predictions of "Roller" element: (a) hover and (b) forward-flight**

***Example Case #2: Triangular elements and tessellation of surfaces of three-dimensional structures/constructs***

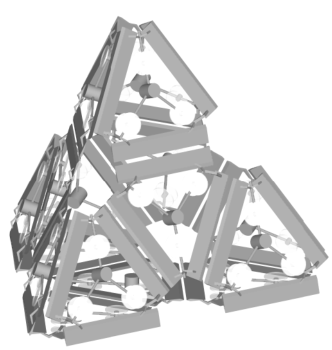
Refer to Fig. 45 as to the possible use of combinations of triangular elements to form two- and three-dimensional constructs.



(a)



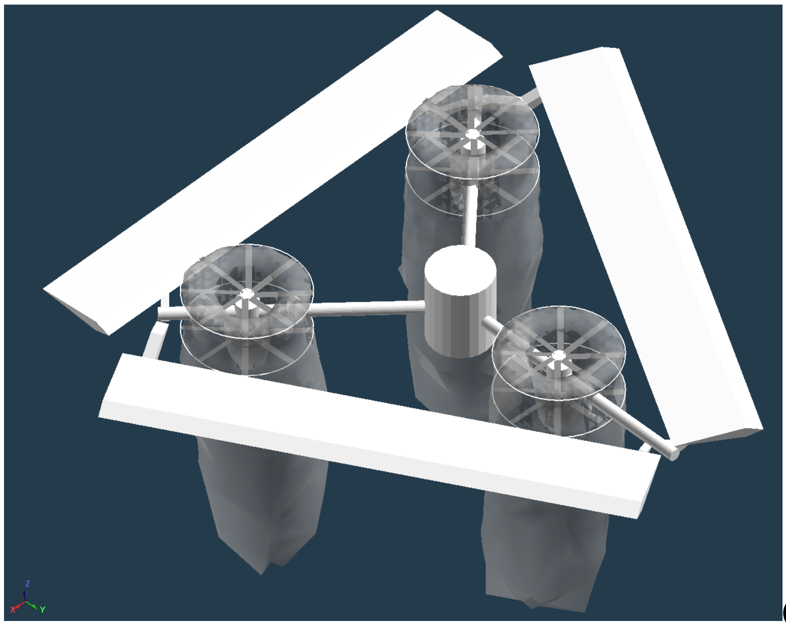
(b)



(c)

**Figure 45. Approach to defining complex surfaces through use of triangular elements for tessellation: (a) coaxial-tricopter (hexacopter) element and (b) a tetrahedral construct**

Some mid-fidelity CFD predictions of both the coaxial-tricopter (aka tricoax) element and a small construct formed from that element, for both hover and edgewise forward flight, is presented in Figs. 46-47.


(a)

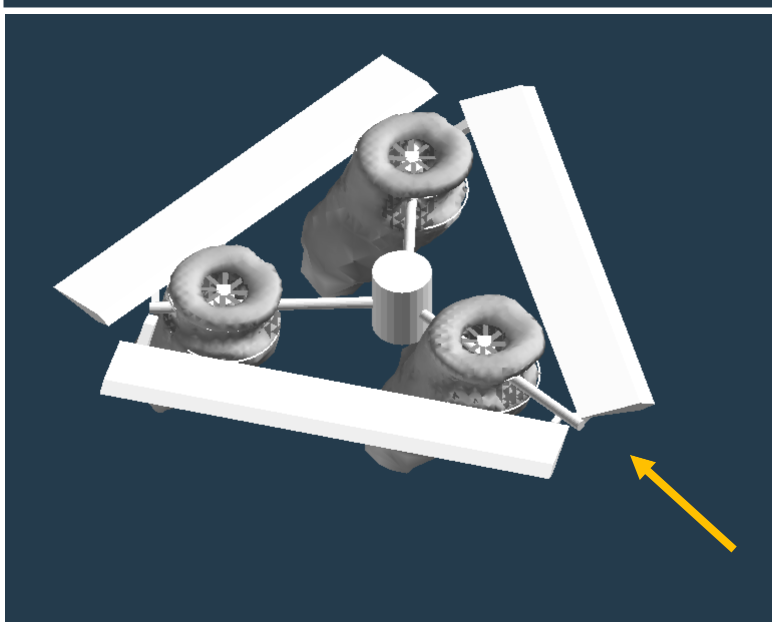
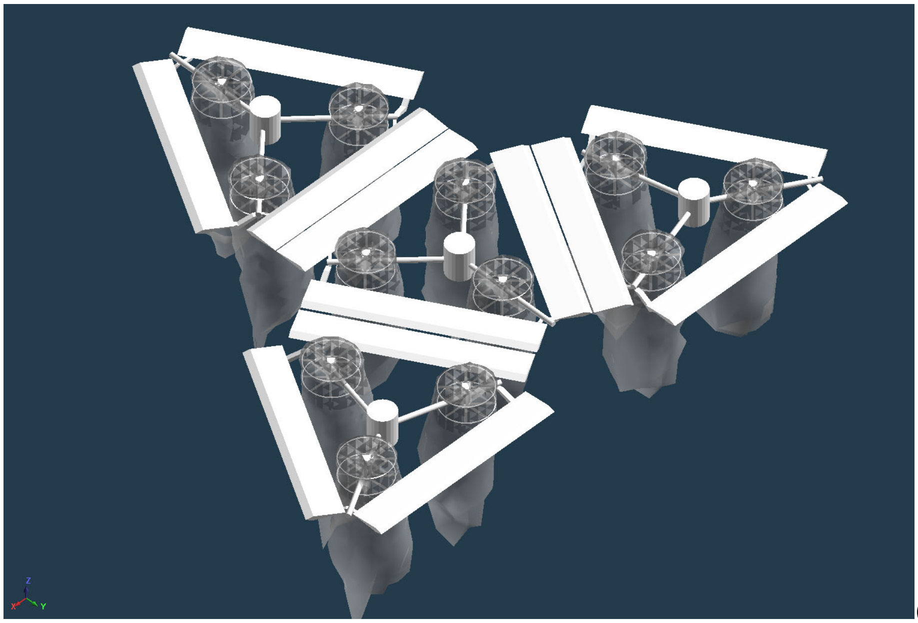
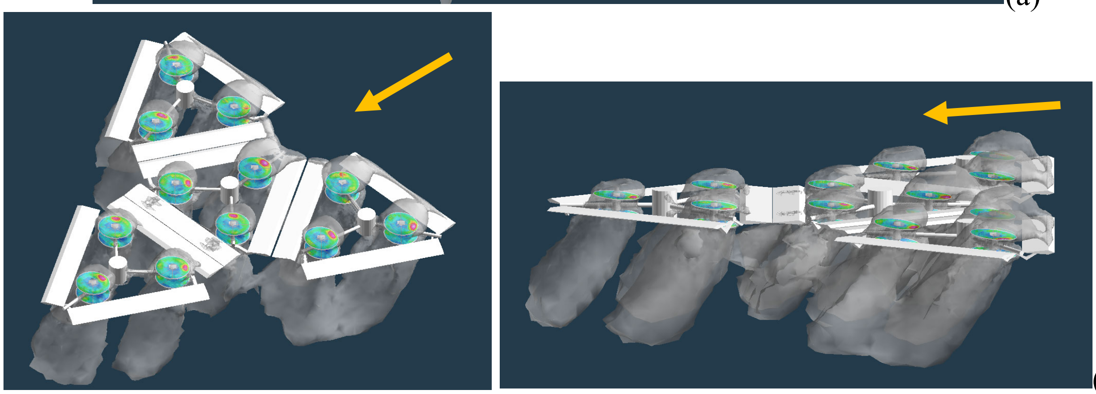
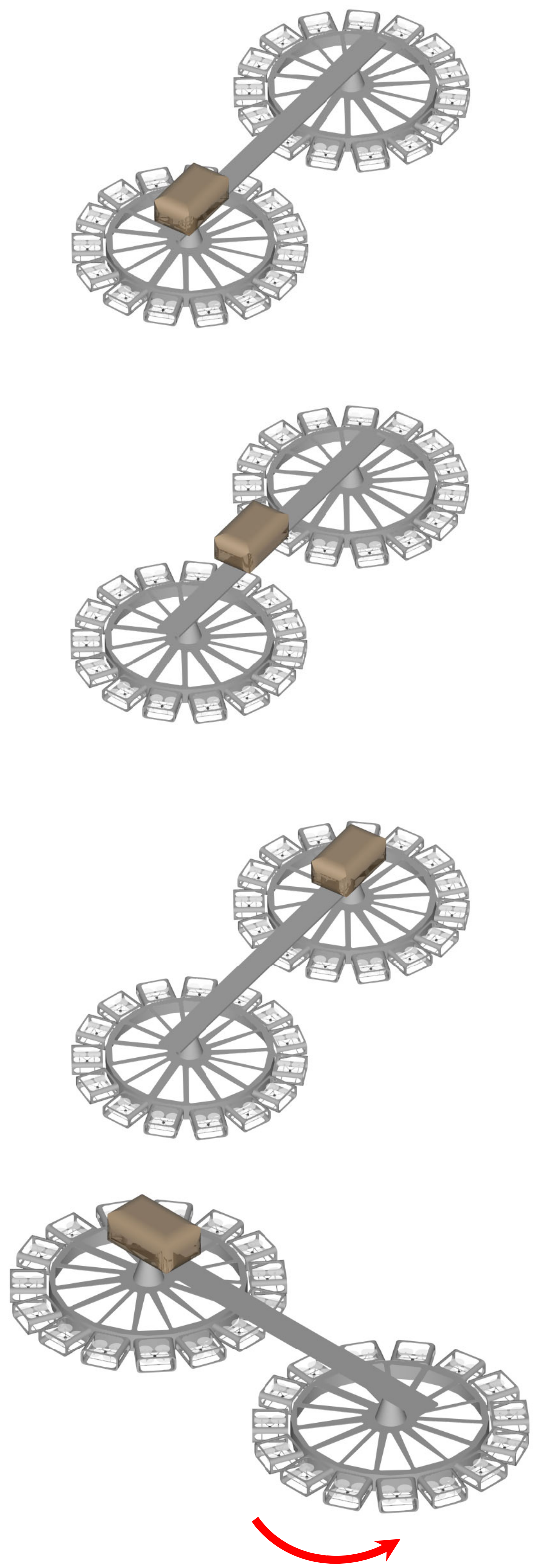

(b)

**Figure 46. Coaxial tricopter element in (a) hover and (b) forward flight**


(a)

(b)
**Figure 47. Coaxial tricopter small construct ('unfolded') in (a) hover and (b) forward flight**

***Example Case #3: Constructs with hybrid air-ground mobility with emphasis on creating large-scale 'simple machines'***

A 'sidewinder walker' hybrid air-ground mobility robotic systems is now described. This concept is composed of UFM elements and nonflying elements. It is one possible novel approach to creating simple machines from (partially) UFME (in this case providing for sidewinder 'walking' ground locomotion). The sidewinder walker concept illustrates the overlap between the UFM concept and the complementary earlier proposed 'rotorcraft as robots' concept (Refs. 11-12).



(a)

(b)

(c)

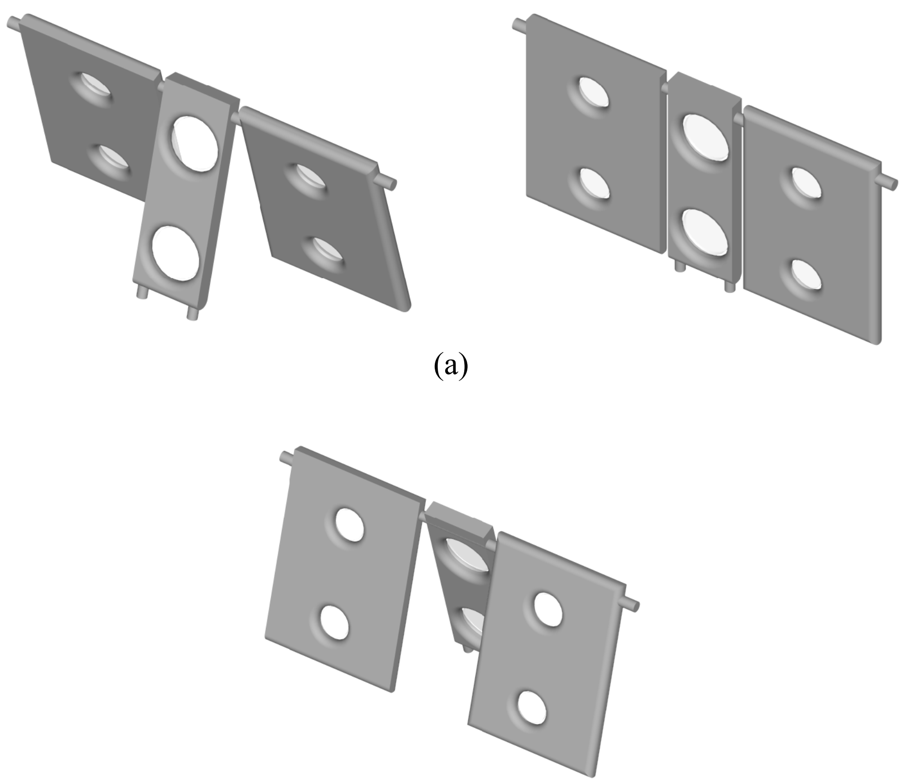
(d)

**Figure 48. 'Sidewinder walker' construct robotic system: (a-d) time steps representing various stages of construct's simple machine ground locomotion**

### *Example Case #4: Rotor-enabled-actuation of a construct 'tripod walker' robotic system*

A new robotics design paradigm can be envisioned wherein instead of using servos and other electromagnetic actuators to effect robotic actuation and manipulation small subassemblies/appendages can be moved by rotors embedded in those same subassemblies.

Except for the rotor-enabled-actuation of each 'leg' of the tripod (versus embedded servomotors), this concept is very reminiscent of a fictional tripod walker used in a recent movie.[2]



(a) (b) (c)

**Figure 49. Tripod walking machine construct using rotary-wing element thrust actuation (time series)**

Figure 50 illustrates the operation of the Tripod walking machine construct concept by providing mid-fidelity CFD rotor wake predictions as a function of time steps.

[2] "Interstellar," Warner Bros., 2014.

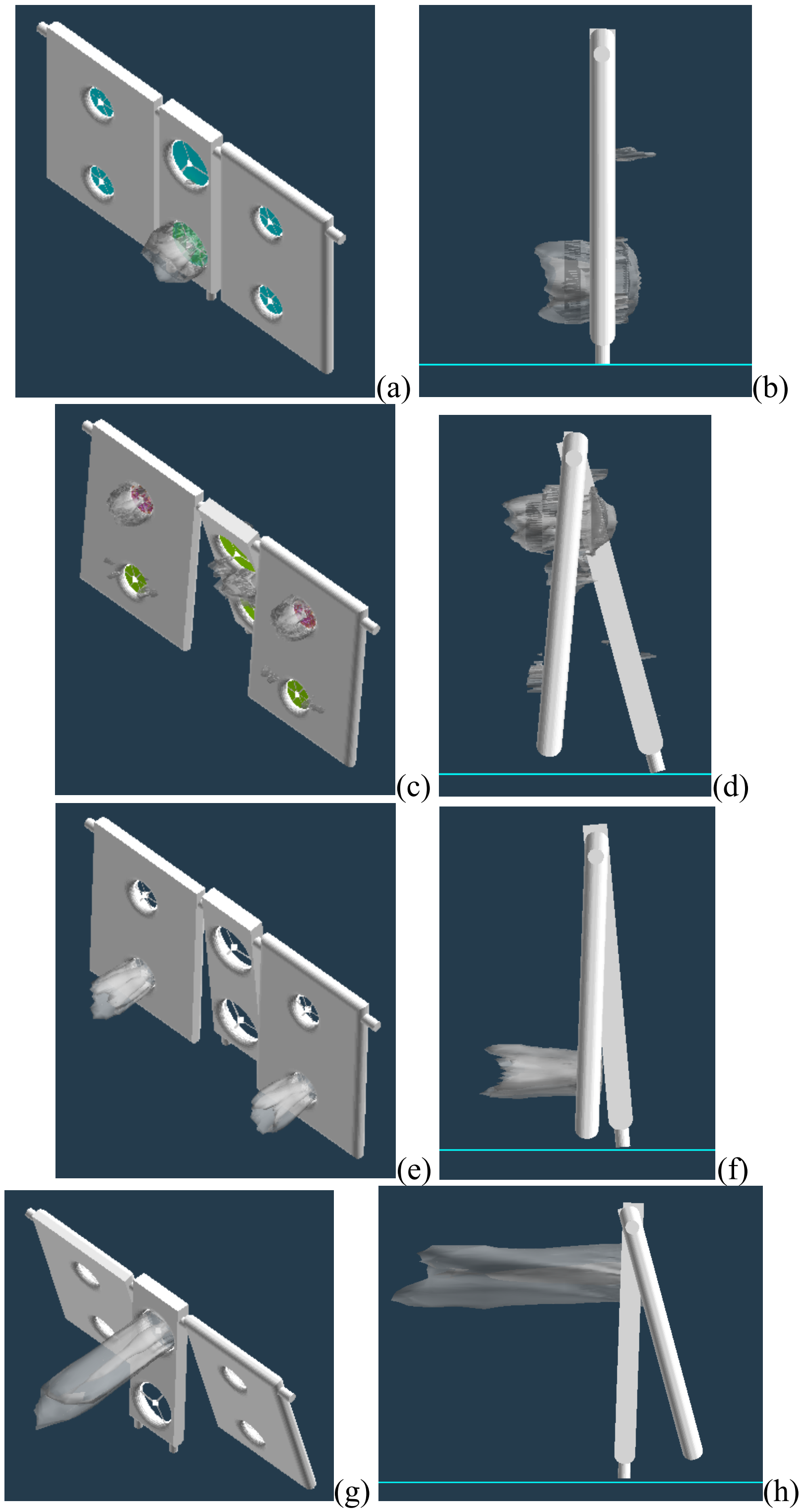



**Figure 50. Tripod walking machine construct mid-fidelity CFD showing rotor wakes for thrusting rotors for actuation of ground mobility: (a-b) step 1, (c-d) step 2, (e-f) step 3, and (g-h) step 4**

*Example Case #5: Space structures – temporary structures formed through use of constructs*

This example case turns from aeronautics applications to space applications. Reference 25 first discussed this concept.

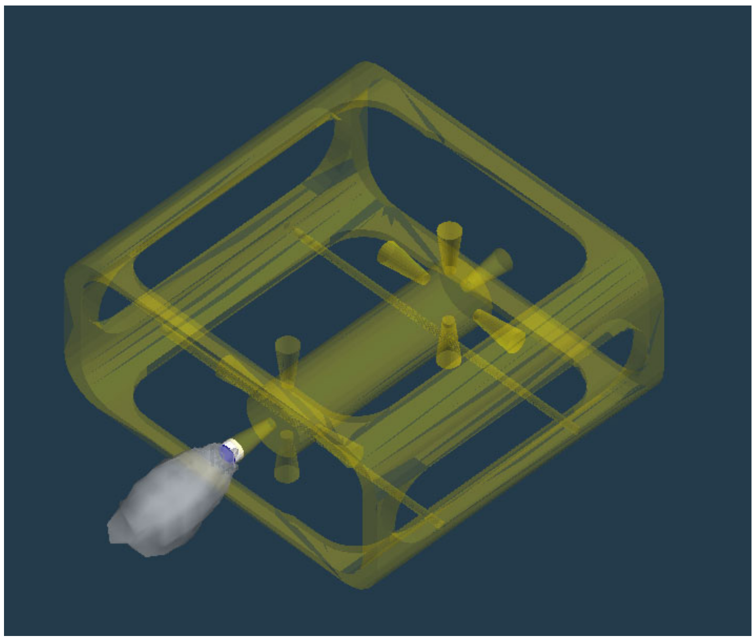


**Figure 51. Space application UFM element (one thruster jet operating)**

*Example Case #6: 'Beads' and 'Pearls' – Simple hybrid air/ground mobility*

'Beads' and 'Pearls' were introduced earlier in the report. Instead of simple linear (tethered or more rigidly attached) arrays of 'beads' and 'pearls' UFME, as previously discussed, the elements can be arranged in (quasi-) continuous loops, refer to Figs. 52-53.

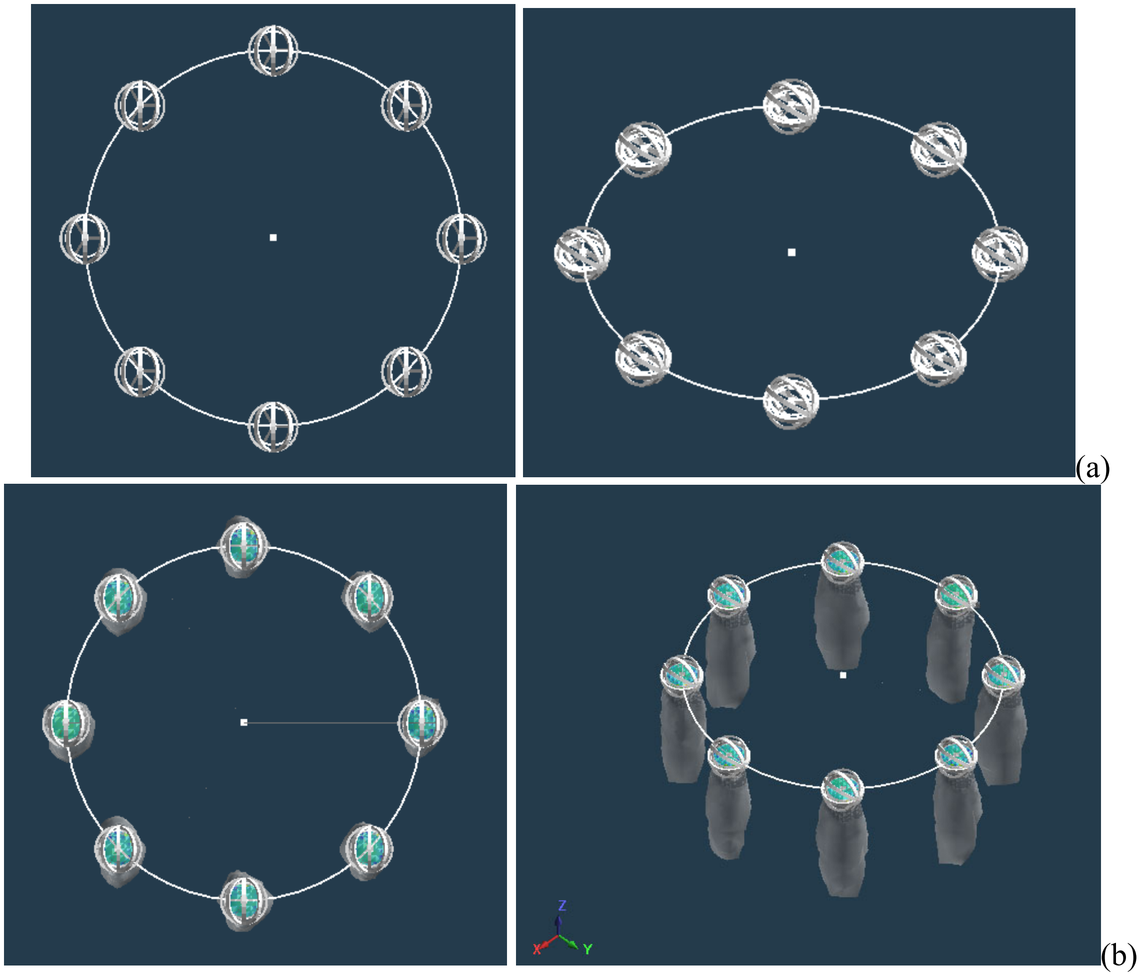
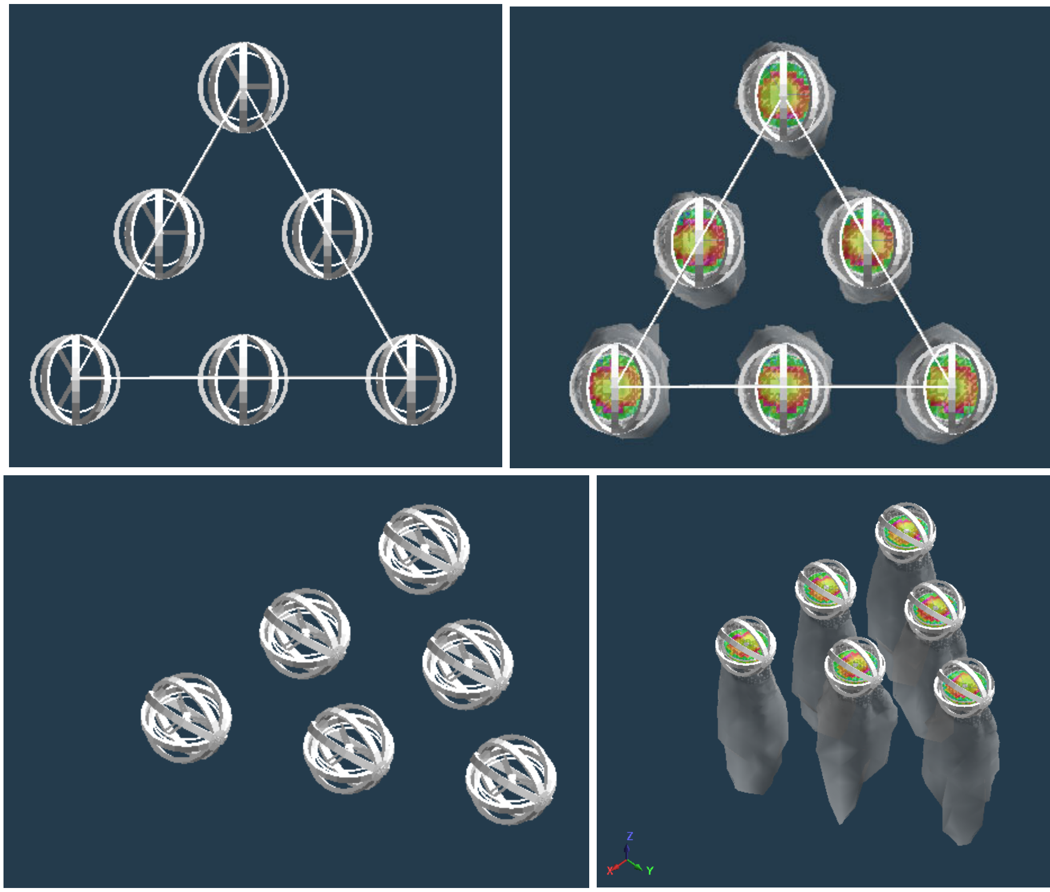



**Figure 52. ‘Necklace’ of ‘beads’: (a) top and isometric view of continuous loop of bead elements and (b) CFD predictions of hovering out of ground effect**

These UFMC ‘loops’ can serve multiple purposes. First, it could allow for the easy transition from a swarm of vehicles to a construct. This transition could be smoothly continuous (by lengthening and or reducing the stiffness of the tethers or cross-arms joining elements) or it could be a discrete change (such as severing the tethers or disconnecting the cross-amrs). Second, the distributed nature of the elements in the construct could allow for an efficient means of carrying external loads. Third, the flexibility of the tethers or low-stiffness cross-arms connecting elements potentially allows for sufficient flexibility to readily enable ‘morphing’ of the overall construct geometry. .



(a)

(b)

**Figure 53. Triangular Loop of 'beads': (a) planform view of CAD and CFD models and (b) isometric view of CAD and CFD models**

***Example Case #7: Constructs with non-edgewise flight capability***

Reference 26 touched upon the potential for modular rotorcraft with non-edgewise flight capability. This focus was primarily on passenger-carrying modular rotorcraft, though, and not UFME or UFMC type modular rotorcraft systems.

This section of the report will briefly discuss UFM constructs that embody partial or fully non-edgewise flight for at least some of portion of flying. There are at least four different types of non-edgewise flight configurations for UFM: (1) constructs with fixed rotors/propellers within the elements; (2) rotor(s) tilting within elements; (3) rotors/elements tilting within cluster or construct; (4) construct tilting as a whole.

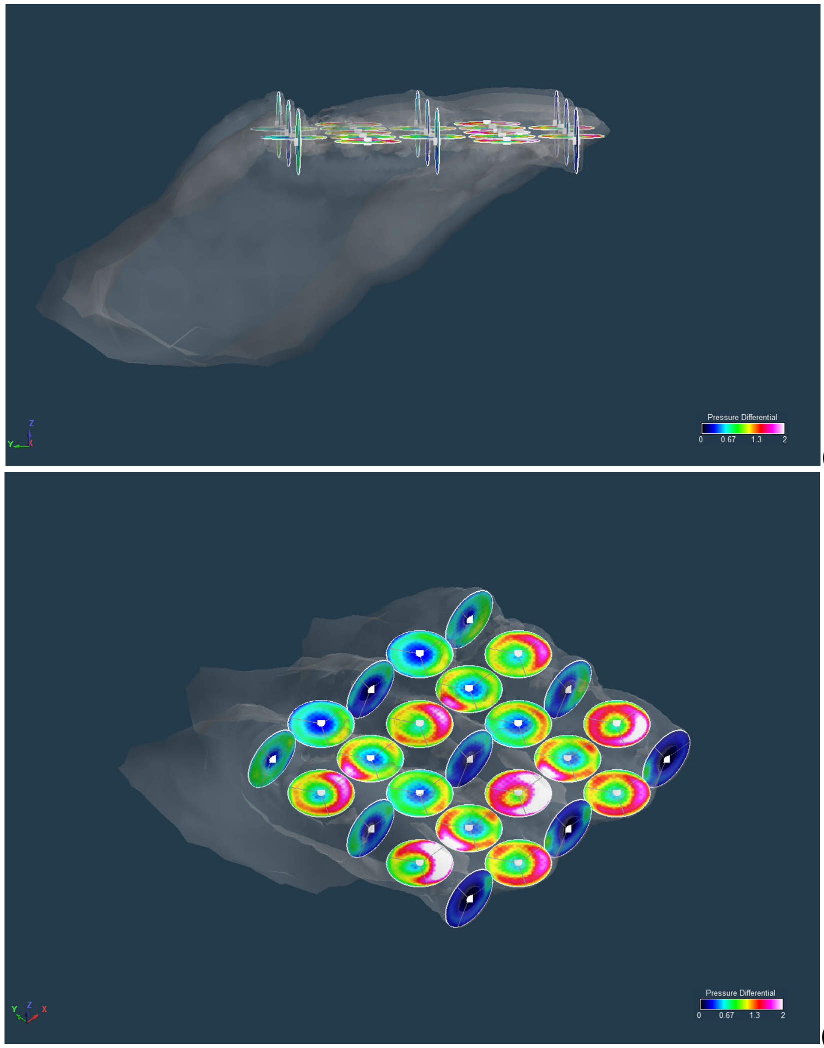



**Figure 54. Example of forward flight with fixed rotors/propellers within elements (mix of 'lifting' versus 'propulsor' rotors/propellers with construct comprised of square matrix of rotors): (a) quasi-side view and (b) isometric view**

Figure 55 considers an extension of the earlier discussed tricoax element and construct concept to include gimballed and/or tilt-mechanism versions of the coaxial rotor sets, such that the coaxial pairs can be tilted into axial/propeller-mode instead of otherwise flying in edgewise (helicopter-mode) flight.

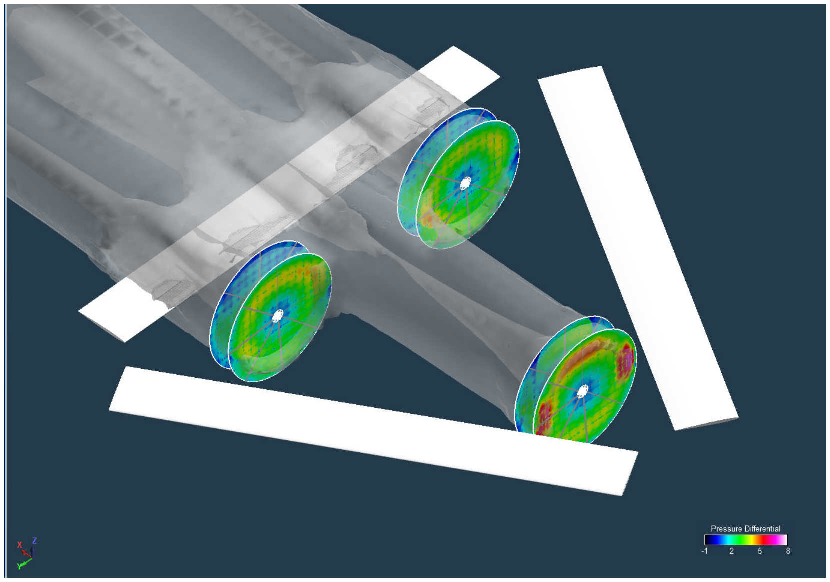
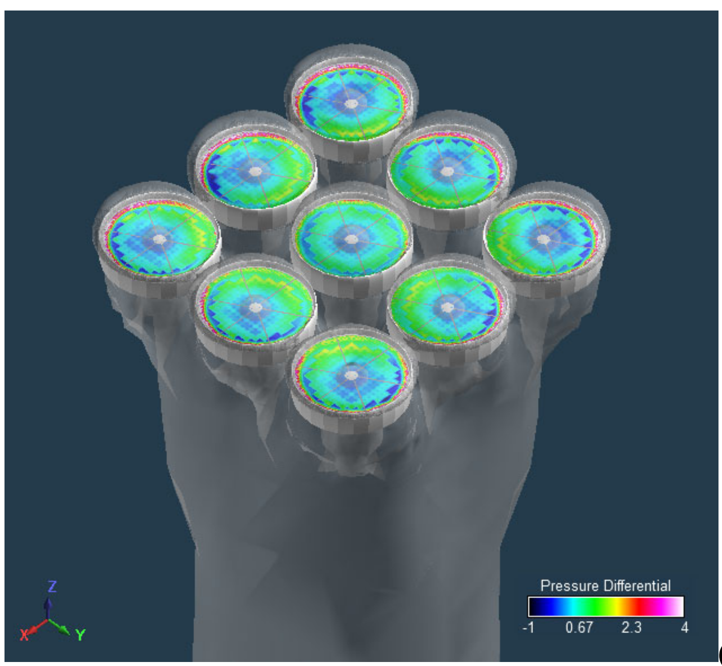
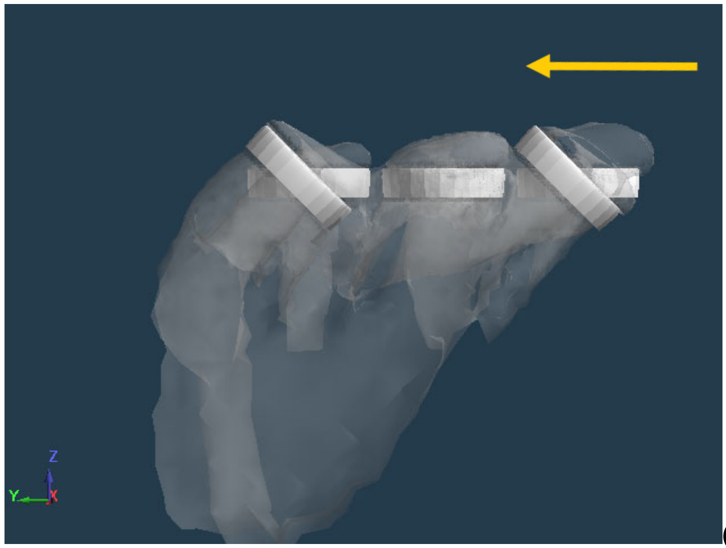



**Figure 55. Example of rotors tilting within elements (tri-coax with tilting propellers in propeller-mode)**

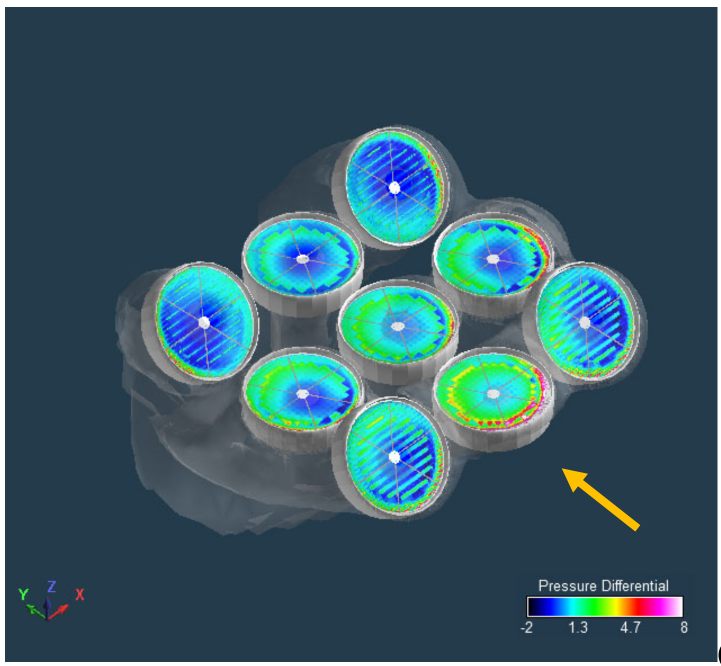
A considerable amount of work was directed towards small autonomous ducted-fan micro air vehicles in the 2000-2010 timeframe, e.g. Refs. 27-29. Figures 56-57 are illustrative examples of potential constructs formed from coaxial-rotor ducted-fan elements.



(a)




(b)




(c)

**Figure 56. Example of rotors/elements tilting within clusters or construct (coaxial-rotor ducted-fan elements, some that tilt and some that do not): (a) isometric view of hover, (b) side view of forward flight, and (c) isometric view of forward flight**

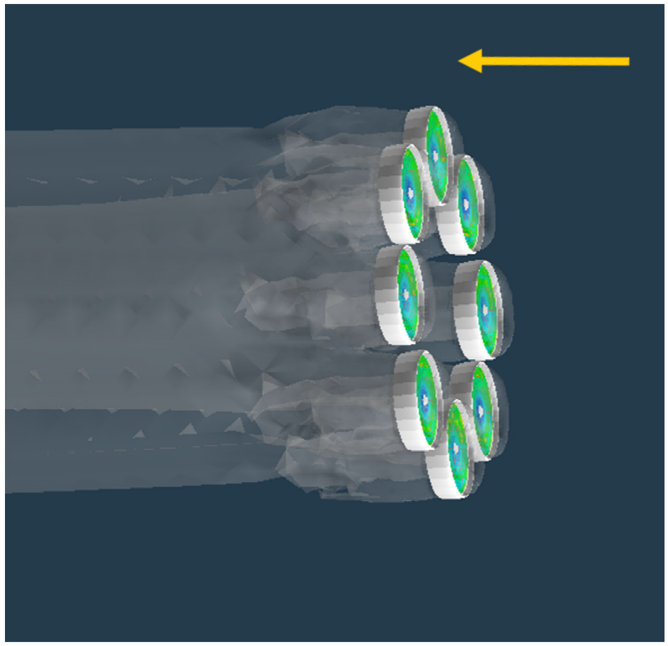


**Figure 57. Example of construct tilting ('ring' of ducted-fans with coaxial-rotors tilted as a whole or construct)**

Finally, Fig. 58 is an example of a 'fixed wing' construct (linear array) formed from elements with turbofans and oval/elliptical tandems, Ref. 26.

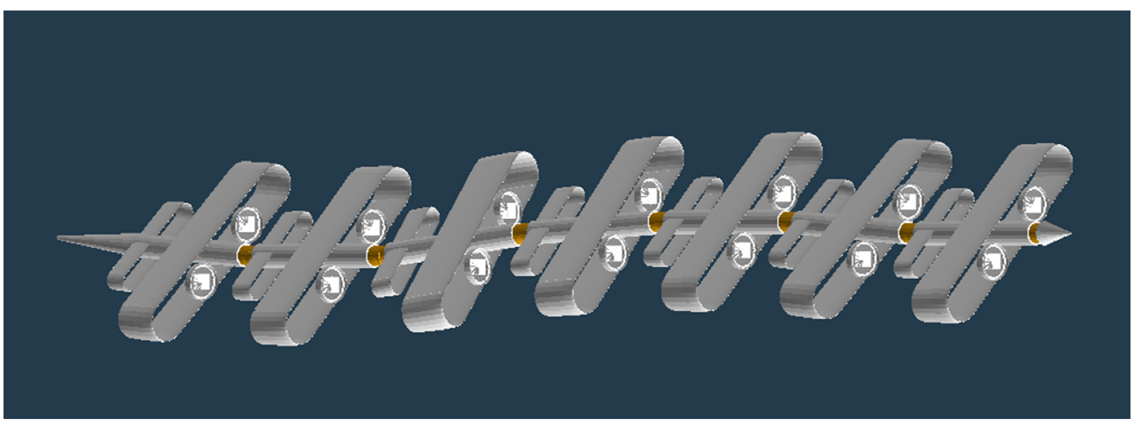


**Figure 58. Example of 'fixed' rotor/propeller non-edgewise forward flight ('Skytrain,' Ref. 26)**

## Concluding Remarks

It is the highest aspiration of technological innovators to constantly test and redefine the boundaries of the plausible and implausible, the possible and the impossible, as to new technologies and new applications. Our history is manifestly full of examples of what was once unimaginable or impossible become considered over the course of time and sometimes great effort being accepted as plausible and then, ultimately, considered realizable, practical, useful, and perhaps even essential.

The universal flying machines concept introduced in this paper is intentionally quite speculative. However, such speculation is, nonetheless, grounded by several emerging technology trends. Instead of being preoccupied by the ‘how’ of making UFM reliable it is more critical to begin to consider the “why” of such aggregate (intertwined or semi-integrated) systems. If enough promising “whys” can be proposed, then efforts towards developing the “how’s” can be justified.

The analogy between universal flying machines and universal Turing machines (between modular aerospace systems and computing machines) was made early on in this report. But there is an additional analogy that could be made between biological systems such as cells, organs, and organisms, and universal flying machines concepts of constructs and elements.

In conclusion, this work seeks to upend any remaining artificial demarcations between robotics and UAV technology to hopefully yield wholly new mission and applications for the aerospace community.

## Acknowledgments

The key contributions of Prof. Ganesh Rajagopalan (dec.), Iowa State University, in developing the mid-fidelity computational fluid dynamics software tool, RotCFD, is gratefully acknowledged. The past collaborative contributions of Mr. Gregory Pisanich on early modular structural concepts and UAVs is also acknowledged. Also, in memoriam, Donald Lee Young. Finally, this report is for all the aerospace engineering innovators who are willing to tackle big ideas that have major cross-disciplinary technical challenges inherent to them.

## References


1. Young, L.A., “A Future for Rotorcraft that Engages with New Application Domains,” Transformative Vertical Flight 2025, 11th Biennial Autonomous VTOL Technical Meeting, Phoenix, AZ, February 4-6, 2025.

2. Aiken, E.W., Ormiston, R.A., and Young, L.A., “Future Directions in Rotorcraft Technology at Ames Research Center,” 56th Annual Forum of the American Helicopter Society, International, Virginia Beach, VA, May 2-4, 2000.

3. Young, L.A., Aiken, E.W., Johnson, J.L., Demblewski, R., Andrews, J., and Klem, J., “New Concepts and Perspectives on Micro-Rotorcraft and Small Autonomous Rotary-Wing Vehicles,” AIAA 20th Applied Aerodynamics Conference, St Louis, MO, June 24-27, 2002.

4. Plice, L., Pisanich, G., Lau, B., and Young, L.A., “Biologically Inspired ‘Behavioral’ Strategies for Autonomous Aerial Explorers on Mars,” IEEE Aerospace Conference, Big Sky, MT, March 2003.

5. Plice, L., “Robot Economy,” Robosphere 2002: Workshop on Self-Sustaining Robot Ecologies, NASA Ames Research Center, Moffett Field, CA, November 2002.

6. Pisanich, G. and Young, L.A., “An Aerobot Ecology,” Robosphere 2002: Workshop on Self-Sustaining Robot Ecologies, NASA Ames Research Center, Moffett Field, CA, November 2002.

7. Young, L.A., Aiken, E.W., and Briggs, G.A., “Smart Rotorcraft Field Assistants for Terrestrial and Planetary Science,” 2004 IEEE Aerospace Conference, Big Sky, MT, March 2004.

8. Pisanich, G., Young, L.A., Ippolito, C., Plice. L., Lau, B., Roush, T., Lee, P., and Thakoor, S., “Initial Efforts towards Mission-Representative Imaging Surveys from Aerial Explorers,” SPIE (International Society of Optical Engineers) Electronic Imaging Conference, San Jose, CA, January 2004.

9. Pisanich, G., Ippolito, C., Plice, L, Young, L., and Lau, B., “Actions, Observations, and Decision-Making: Biologically Inspired Strategies for Autonomous Aerial Vehicles,” To be presented at the AIAA Aerospace Sciences Conference, Reno, NV, January 2004.

10. Decentralized swarm control; https://spectrum.ieee.org/automaton/robotics/robotics-hardware/swarm-of-robots-forms-complex-shapes-without-centralized-control?utm_source=techalert&utm_medium=email&utm_campaign=techalert-03-19-20&mkt_tok=eyJpIjoiWkRZeVptTmtOemswTURRMiIsInQiOiJqSVZSQ3VyVDZPR0RkNDFSSVJyckppZ0ZmN1YyOUVqSk9RTmN2N2kyaVRJRTlcL1JxaTh6YWNYUHUyU2c4bVwvZjFYb3BRbTZwSWRTTDQ0U20wMlcrdU5BMFZZbVZJSVwv

VDJcL1VLMDNvYkdoa3NyWG93ZG81Vk9JWGtsb09aRjNOcFVMdFhRUUlvZWhaXC9nU2VTVmVlQ1JBdz09In0%3D; last accessed March 19, 2020.

11. Young, L.A., Young, L.A., "Rotorcraft as Robots," San Francisco Bay Area Chapter of the Vertical Flight Society webinar; https://www.youtube.com/watch?v=A843t70amxA; last accessed February 27, 2025.

12. Young, L.A., "Rotorcraft as Robots," NASA TM (Soon to be published).

13. Caltech bipedal robot using quadcopter for balance; https://www.theverge.com/tldr/2019/10/7/20903112/leonardo-drone-bipedal-robot-balance-propellers-video; last accessed February 28, 2020.

14. University of Tokyo bipedal robot using quadcopter for balance; https://www.theverge.com/2018/8/16/17698186/aerial-bipedal-robot-buoyancy-quadcopter-university-of-tokyo; last accessed February 28, 2020.

15. Agha-mohammadi, A., et al, "The Shapeshifter: a Morphing,Multi-Agent, Multi-Modal Robotic Platform for the Exploration of Titan," NIAC (NASA Innovative Advanced Concepts program) Phase I Final Report, May 31, 2019; https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190033457.pdf; last accessed March 2, 2020.

16. Combined quadcopter and 'flying squirrel' design; https://www.msn.com/en-us/news/technology/this-flying-squirrel-drone-can-brake-in-midair-and-outsmart-obstacles/ar-AA1E4BPG?ocid=msedgdhp&pc=U531&cvid=67d805d94e0b4e8cb408ea4fb62be225&ei=27; last accessed May 17, 2025.

17. Ackerman, E., "Flying Dragon Robot Transforms Itself to Squeeze Through Gaps: DRAGON can change its shape to move through complex environments and even manipulate objects," IEEE Spectrum, June 20, 2018; https://spectrum.ieee.org/flying-dragon-robot-transforms-itself-to-squeeze-through-gaps; last accessed July 18, 2025.

18. Young, L.A., "Conceptual Design Aspects of Three General Sub-Classes of Multi-Rotor Configurations: Distributed, Modular, and Heterogeneous," Sixth AHS International Specialists Meeting on Unmanned Rotorcraft Systems, Scottsdale, AZ, January 20-22, 2015.

19. Turing, A.M. 1936 in The Undecidable 1965.

20. Drone with life preserver saves person caught in riptide; https://www.youtube.com/watch?v=kH5PIBPlzXA; last accessed July 21, 2025.

21. Linked together, small ground mobile robots; https://www.msn.com/en-us/news/other/researchers-build-next-gen-swarm-robots-that-move-and-cooperate-without-code-or-sensors/ar-

AA1EuUoz?ocid=msedgdhp&pc=U531&cvid=e5a4f5c8e8d34bcc9b1760facf9ed0ce&ei=101; last accessed May 29, 2025.

22. Spherical air/ground robot; https://www.youtube.com/watch?v=1yqN18VBenw; last accessed July 21, 2025.

23. Rajagopalan, R.G., Baskaran,V., Hollingsworth, A., Lestari, A., Garrick, D., Solis, E., Hagerty, B., "RotCFD - A Tool for Aerodynamic Interference of Rotors: Validation and Capabilities", AHS Future Vertical Lift Aircraft Design Conference, January 18-20, 2012 San Francisco.

24. Rajagopalan, G., Thistle, J., Polzin, W., "The Potential of GPU Computing for Design in RotCFD," AHS Technical Meeting on Aeromechanics Design for Vertical Lift, Holiday Inn at Fisherman's Wharf, San Francisco, CA, January 16-18, 2018.

25. Young, L.A., Aiken, E.W., "Exploration: Past and Future Contributions of the Vertical Lift Community and the Flight Vehicle Research and Technology Division," AIAA 1st Space Exploration Conference, Orlando, FL, January 30-February 1, 2005.

26. Young, L.A., "Building Enhanced Resilience into Aviation," Transformative Vertical Flight 2025, 11th Biennial Autonomous VTOL Technical Meeting, Phoenix, AZ, February 4-6, 2025.

27. Ko, A., Ohanian, O.J., and Gelhausen. P., "Ducted Fan UAV Modeling and Simulation in Preliminary Design," AIAA 2007-6375, AIAA Modeling and Simulation Technologies Conference and Exhibit, Hilton Head, South Carolina, August 20-23, 2007.

28. Johnson, E.N. and Turbe, M.A., "Modeling, Control, and Flight Testing of a Small Ducted-Fan Aircraft," AIAA JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS, Vol. 29, No. 4, July–August 2006.

29. Kubo, D., Nagasaka, N., and Suzuki, S., "Autonomous Distributed Aerial Observation System Using Electric Ducted Fan Micro Aerial Vehicles," AIAA 2009-1968, AIAA Infotech@Aerospace Conference, Seattle, Washington, April 6-9, 2009.