Rotorcraft and Enabling Robotic Rescue

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***Abstract* – This paper examines some of the issues underlying potential robotic rescue devices (RRD) in the context where autonomous or manned rotorcraft deployment of such robotic systems is a crucial attribute for their success in supporting future disaster relief and emergency response (DRER) missions. As a part of this discussion, work related to proof-of-concept prototyping of two notional RRD systems is summarized.**

Index Terms* – *rotorcraft; helicopter; disaster relief; emergency response; UAV; autonomous; robotic; systems analysis; conceptual design.

I. Introduction

Rotorcraft provide an unparalleled aviation capability for disaster relief and emergency response (DRER) efforts. However, recent advances in autonomous systems and robotic technologies promise to revolutionize rotorcraft DRER efforts. Many researchers have proposed addressing the evolving demands of emergency response and disaster relief support, in part, through the use of robotic rescue devices (RRD). One key constraint is the transportability and operability of such systems. In this regard, rotorcraft transport and operation of robotic rescue devices is a potentially powerful new approach. In support of this new DRER paradigm, this paper will, in part, perform a high-level discussion of various notional robotic rescue devices where rotorcraft deployment, manned or autonomous, is a crucial attribute. It builds upon previous work, e.g. [1-13], conducted at NASA Ames in the areas of DRER mission analysis, autonomous aerial vehicle development, and robotic systems research in general.

In addition to the qualitative system assessment discussion that will be presented, some initial proof-of-concept work will also be detailed for two notional robotic rescue devices: a "Vectored" rescue hoist [3] and a "Merman" water rescue system [1]. The paper concludes with a discussion of other points of interest with respect to the public service application of advanced rotorcraft technologies -- for example, recent work being performed such as that reported in [16-17]. In short, this paper examines the synergies of advanced rotorcraft – and autonomous/robotic system – technologies in the context of life saving activities, consistent with the unique goals of the Heli Japan series of meetings.

A. Potential Disaster Relief and Emergency Response Missions

The following notional DRER mission table is taken from [2]. It reflects tasks that could be supported by autonomous aerial vehicles and rotorcraft paired with robotic rescue systems. A key objective in developing this mission task list is to help define new technologies and vehicle/systems concepts for future DRER missions.

TABLE I – Representative Disaster Relief Missions/Tasks

Mission #1 (SAR, Search and Rescue) – *Ground taxiing; runway or vertical TOL; cruise to search area; maintain communications with multiple assets; perform in-flight situational awareness and collision avoidance monitoring; over-flight of prescribed search pattern; communicate location of target if acquired; return to base upon location of target or need for refueling.*
Mission #2 (Damage/Recovery Surveys) – *(All of the above, plus tasks noted below)* #2A (Aerial Survey Only) – *Perform over-flight of not only prescribed waypoints & target search areas but to engage in active/adaptive search using an assortment of flight behaviors; perform in-flight damage assessments using heuristic analysis techniques, as well as relay raw data and assessments back to home base. .* #2B (Surface Interaction) – *VTOL at remote sites, under unknown and uncertain conditions; air-deploy, as need be, sensors and devices over targets of interest; ground-deploy, as need be, sensors & devices; perform sampling and other manipulation of the immediate environment of the vehicle while on the ground; exert ground/surface mobility (in a hybrid sense) as need be; automated servicing and maintenance pre- & post-missions.*
Mission #3 (Utility Transport of Equip/Supplies) – #3A (Basic Relief Supplies) – *Ground taxiing; runway or vertical TOL; cruise to remote relief camp; maintain communications with base and relief camp; perform in-flight situational awareness and collision avoidance monitoring; remote site*

[1] Presented at Heli Japan 2010, Saitama, Japan, November 1-3, 2010.

(rough & short-strip) runway or vertical TOL, under largely uncontrolled and uncertain conditions; deploy supplies to authorized camp personnel; highly automated (internal) cargo handling equipment; interaction with potentially inadequately trained relief workers or local authorities. #3B (Heavy/Specialized Equipment; Internal Stored) – *(All of the above, plus tasks noted as follows); automated deployment of equipment, including (relayed from base) teleoperation of self-propelled equipment driven off vehicle.* #3B (Heavy/Specialized Equipment; External Slung Load) – *VTOL required; cargo handling automation & devices capable of safely attaching and/or releasing slung loads at remote sites by potentially untrained (or even non-present) ground personnel.* #3D (Automated/Robotic Rescue Equipment) – *VTOL required; deployment (air & ground and with & without ground personnel assistance) robotic rescue devices (and, as need be, control systems); loiter and support (networking/communication and control of rescue devices from the air.*
Mission #4 (Medical Transport) – *VTOL required for aerial transport; advanced human-system-interaction, including telepresence, to provide safe and effective implementation or maintenance of care in-flight; specialized automated, and perhaps robotic, medical systems for advanced in-flight care.*
Mission #5 (Refugee Transport) – *Runway or Vertical TOL; (novice) human-system-interaction, including telepresence, to provide safe and supportive embarkation, disembarkation, and in-flight comfort and care.*
Mission #6 (Security/Stabilization) – *Deployment (air & ground) of sensors, devices, and robotic (and non-robotic) security assets to insure safe and effective relief distribution -- even in the face of unpredictable, or even openly hostile, elements.*

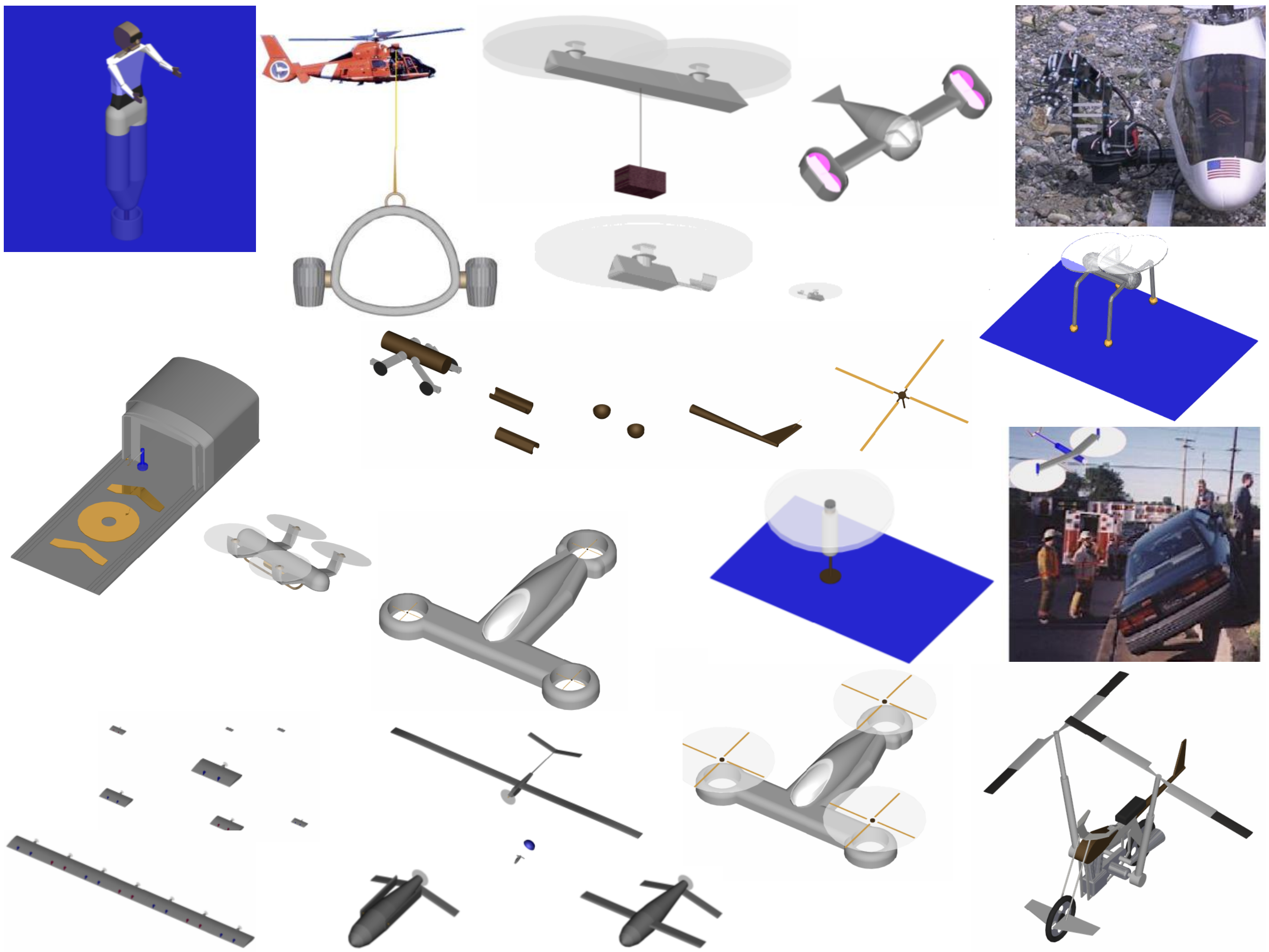
B. Potential Robotic Rescue Devices and their notional Interaction with Rotary-Wing Vehicle Assets

Experience over the past couple of decades has highlighted the increasing mission demands for rotary-wing assets to support disaster relief operations throughout the world. Commensurate with this increased demand for aviation assets -- as well as other resources -- is a complementary increase in public expectations as to the timeliness and effectiveness of the response efforts. These mission demands and expectations can be anticipated to only grow with time.

Ideally, advancements in DRER mission capabilities and concepts of operation should be directed to all three major phases of disaster relief missions: the pre-disaster planning/staging phase, the response phase, and the recovery phase. How, or does, technology (specifically autonomous aerial vehicles and intelligent/robotic systems) contribute to enhanced DRER mission capability? Further, is there a need for technological innovation and research and development to address the "application domain" of disaster relief and emergency response? These are questions that ideally systems analysis that incorporates the key application domains of rotary-wing vehicles, robotic/intelligent systems, and operations research can ideally address.

Why concern ourselves with the pros and cons of advanced technologies to meet future disaster relief challenges when clearly there are so many compelling requirements for even the most basic of resources and equipment here and now? The following considerations are offered for studying disaster relief and emergency response operations as a research and technology application domain: 1. arguably this is an under-served application domain with respect to technology investment (given the relative importance, and visibility with respect, to the general public); 2. Support of disaster relief efforts are often seen as a level-of-resource issue and not as a technology issue and, yet, technology investments would ideally be directed to maximize response/relief efficiency and thus reduce overall resource requirements over time; 3. Disaster relief efforts have mostly relied on, or leveraged non-dedicated-public-service (commercial and military) aerial assets; 4. It is the contention of this paper that new emerging technologies – i.e. intelligent and robotic systems tailored to DRER missions -- are poised to make significant advancements; 5. This application domain makes a compelling system analysis topic given the limited attention focused to date on this topic area as well as the unique constraints, metrics, and goals/objectives underlying this domain.

Can technology be leveraged to define improved strategies for providing adaptive, efficient and effective, responses to both the small emergencies and large catastrophes? How can this question best be analytically addressed or studied? To proceed in addressing these questions, an identification of the "societal good" goals must first be performed. What are these societal good goals then (the need for improvement over the status quo) underlying disaster relief and emergency response missions? It is proposed [2] that this societal good goal can be expressed as*: to save all those who can be saved, to provide relief to all those who suffer, irrespective of the size of the disaster or the remoteness or inaccessibility of those who need help.* Commensurate with this goal are the following application objectives: 1. Improved safety for rescue/recovery efforts both for response teams and victims; 2. Faster, and more comprehensive, response to even the most inaccessible locations, while under severe operational or environmental conditions, and daunting infrastructure limitations; 3. Flexible scalability of response to meet even the greatest of relief/emergency challenges; 4. Efficiency in usage/distribution of limited/high-value resources; 5. Maximize survivability of victims; 6. Minimize property/infrastructure damage (through pre- and post-incident actions); 7. Expedite recovery through optimum damage/security surveys and (re-)distribution of resources and overall aid; 8. Do all of the above while maximizing affordability of the assets/equipment employed and resources expended during the overall response; 8. Provide wholly new and/or unprecedented capabilities and services to the response/recovery effort.



Fig, 1 -- Sample Spectrum of Autonomous Aerial Vehicle and Robotic Rescue Device Concepts (concepts drawn from [1-2])

Table II illustrates how DRER missions – such as those identified in Table I – might be matched to various notional RRD system concepts. The robotic rescue device concepts are drawn from [1-4, 17, 20]; this is, of course, not an exhaustive list of RRD-type concepts but is of sufficient breadth to illustrate the potentiality of such systems for DRER missions. The intent of this matching of DRER mission tasks to vehicle/system concepts is not to advocate for any given concept but, instead, to initiate a much-needed dialog among aerial vehicle and robotic system researchers and developers as to the possible synergistic effects of mutually developing systems-of-systems to address future DRER needs.

TABLE II – Matching of DRER Missions with Notional Autonomous Vehicle and/or RRD Concepts

Mission Phase	**Autonomous Vehicle & RRD Tasks**	**RRD Concepts that could support Mission/Task**
SAR, Search and Rescue	Urban rescue; high-rise buildings	Vectored rescue hoist [1, 3]
	Water rescue	Merman system [1]; “Interface” air/sea system [1]
	Collapsed building/debris rescue	“Damsel fly” hybrid ground/air robotic mobility [2]; micro-rotorcraft with robotic actuators/effectors [2]
Damage/Recovery Surveys	Rapid, targeted aerial surveys	“Fractal flyer” [1]; “Aerial surveyor”

		mothership/daughter ship UAVs [4]; Sentinel networks [2]
	First-responder access to sites inaccessible to conventional ground transportation (damaged roadways; flooded areas; etc.)	Hybrid hovercraft/rotorcraft systems [2]; "road-able" rotorcraft [2]
	Rapid insertion of critical first-responder teams	High-speed, optionally-piloted VTOL platforms (e.g. ducted-fan, twin-nacelle powered lift vehicles) [2]
Utility Transport of Equip/Supplies	Rapid supply delivery in uncertain territory and/or circumstances	Modular, autonomous vertical lift (e.g. modular tandem/coaxial rotary-wing platforms) [2]
	Shortages of specialized debris and victim recovery equipment	Small ("right-sized") teleoperated/semi-autonomous debris/recovery equipment [22]
Medical Transport	High-speed, targeted delivery of medical assistance	Small autonomous high-speed VTOL platforms delivery medical supplies and/or advanced, fieldable telemedicine systems [2]
	Efficient, timely removal of injured	Optionally-piloted and/or autonomous VTOL platforms specifically designed for medevac
Refugee Transport	Timely and efficient evacuation	High-speed VTOL [17, 20]; hybrid manned ground/air systems [2]
Security/Stabilization	Surveillance	"Fractal flyer" [1]; "Aerial surveyor" mothership/daughter ship UAVs [4]; Sentinel networks [2]; "Interface" air/sea system [1]

C. *Implications for Rotary-Wing Vehicle Design*

In an ideal sense the development and application of RRD systems for DRER missions – transported, operated, and/or otherwise enabled by rotorcraft platforms – will also ultimately influence rotary-wing vehicle design. One probable example of how disaster relief missions might influence rotary-wing vehicle design is that such mission considerations will likely contribute to an acceleration in the development by the rotorcraft industry of optionally-piloted and autonomous rotary-wing platforms. Two other rotary-wing design trends also seem probable: (1) advanced/exotic VTOL technologies/configurations finding their initial realization more and more with autonomous aerial vehicle demonstrators rather than manned platforms and (2) the emergence, or perhaps more correctly resurgence, of concepts exploring hybrid ground/aerial mobility, i.e. "road-able" rotorcraft.

II. Further Thoughts Regarding Design and Analysis of Rotorcraft-Enabled Robotic Rescue Systems

There is only a limited body of publically available formal operations research and/or systems analysis work directly applicable to the problem of efficient/effective deployment of rotorcraft assets for disaster relief and large-scale emergency responses. One recent exception is the work of [23]. This is a critical area for future research. Such research would have manifold benefits; it could, for example, lead to improved concepts of operation for relief efforts. It could also be used to define mission and functional design requirements for a new generation of equipment for relief missions – including the rotorcraft-enabled robotic rescue systems advanced in this paper.

A. *Metrics*

It is difficult to conduct systems analyses for application domains where widely-recognized performance metrics are hard to come by. There appears to be no universally recognized scale or measure for disaster relief planning. In the particular case of rotorcraft being used to support DRER efforts employing robotic rescue devices/systems a number of potential metrics can be offered: (1) time to initial coordinated response; survey area covered per unit time; (2) number of rescues mounted per unit time; (3) mean delta time from victims being found to critical aid being rendered; (4) dispersal rate of aid supplies (resources distributed per unit geographic area, per unit population, per unit time); etc.

B. *Critical Technologies*

Table III summarizes some of the anticipated critical technologies required to realize the RRD systems illustrated in Fig. 1, summarized in Table II, and previously discussed in more or less detail in [1-5]. The emphasis of Table III is to highlight both the breadth of technologies that might be required as well as identifying common technologies applicable to several of the notional RRD systems.

TABLE III – Some Critical Technologies for Autonomous Vehicles and RRD Concepts

Autonomous Vehicle and/or RRD Concepts	Anticipated Mission Capabilities	Critical Technologies
"Merman" water rescue system [1]	High-risk water rescues	Extensive robotics development; some modest hydrodynamics research; significant human/machine interface research.
"Vectored" rescue hoist [1, 3]	Rescue lift capability from otherwise inaccessible recovery sites	Significant ducted-fan aerodynamics and control system research; modest robotics/teleoperation research.
"Sentinel" networks [1]	Pre-staging of critical aerial survey and surveillance assets in high-risk potential disaster sites (i.e. Forest Service fire-spotting)	Modest rotary-wing vehicle development; significant research into robotic system-to-system coordination research
"Fractal Flyers" [1]	Rapid aerial surveillance that can be tailored to high and low altitude observations as well provide a distributed perspective	Modest aerodynamics/vehicle development effort; significant distributed control system research; significant robotic system-to-system coordination research.
"Aerial Surveyor" [4]	Same as above	Significant aerodynamics/vehicle development effort; significant distributed control system research; significant robotic system-to-system coordination research.
Modular Rotary-Wing Platforms [2]	Optimizing aerial assets, and required support personnel, for relief response	Significant aeromechanics research and vehicle development; significant advances in avionics and automation.
High-Speed VTOL [2]	Rapid first-responder response	Significant research into aerodynamics, aeromechanics, and vehicle development.
"Damsel-Fly" [2]	Rapid ground survey at disaster sites	Significant research into adaptive systems.
Micro-rotorcraft with robotic arms/effectors	Same as above	Modest robotics research.
Road-able rotary-wing platforms [2]	Rapid first-responder response	Significant vehicle development; uncertain aeromechanics issues.
Mobile Telemedicine Triage System [2]	Providing critical life-or-death first-aid in the minimum possible time	Significant medical, robotic, and telecommunication and teleoperation research required; critical safety issues to address
(Small) tele-operated/semi-autonomous debris removal equipment [22]	Address critical specialized equipment, and operator expertise, shortages	Modest mechanical system development; significant research into robotics, teleoperation, human-machine interface issues.

C. *Rotorcraft as Crucial Enabling Platforms*

In addition to robotic rescue devices/systems discussed in [1-3], as noted above, several other researchers, principally from the robotics community, are attempting to develop such systems. However, given the limited mobility of unmanned ground vehicles, and other non-flight-capable, robotic systems, it is asserted in this paper than an essential element of their ultimate success is to couple such systems to aerial platforms – for their transport, operation, and overall support. The logical aerial platform of choice is rotorcraft for DRER-type missions. But it is more than just a question of transport of these systems. To fully realize the success of RRD in DRER missions, rotary-wing assets will have to be transformed into operational centers and/or communication nodes for the operation these deployed systems.

D. *The Necessity of Simulation-Based Analysis*

Though technology demonstrations and operational exercises are an invaluable means of evaluating the late-stage maturation of technologies, much of the groundwork for the development of rotorcraft-enabled robotic rescue system will have to rely upon simulation-based analysis.

Simulation-based analysis is already pervasive in both the rotorcraft and robotics community. However, what is required, and what is to date undeveloped, is the ability to perform specialized systems-of-systems simulation studies, incorporating both types of systems, focused on defining/refining mission/functional requirements and concepts of operation for such coupled systems. Such systems-of-systems analysis is essential.

E. *Two Disparate Research Communities and the Need for Joint Participation into Technical Demonstrations*

The dialog to date between the robotics and rotorcraft research communities is, at best, extremely limited and restricted mostly to developing/enhancing the autonomy of the rotary-wing asset itself. Very little discussion has been initiated so far on the notional paradigm of rotorcraft cooperatively working with robotic assets. Despite this lack of dialog to date, as outlined in this paper and earlier companion works [1-2], there are nonetheless compelling reasons for both research communities to explore common interests and technologies for DRER applications.

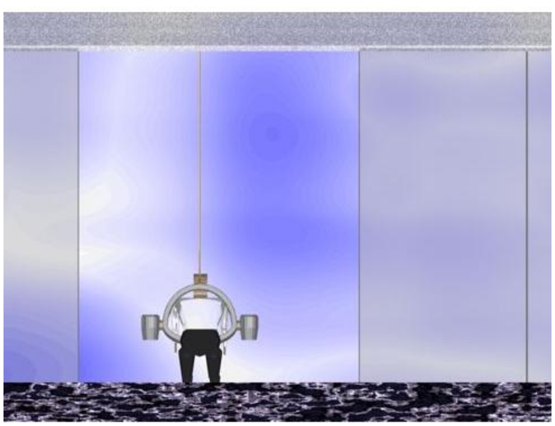
Finally, it is a key assertion of this paper that there can be a mutual leveraging of development efforts for more mission capable systems for both robotics and rotorcraft.

The remainder of the paper will now consider some of the pragmatic implications of the above systems analysis by performing limited proof-of-concept investigations of a couple notional robotic rescue devices: the "Vectored" rescue hoist and the "Merman" water rescue system. .

III. CONCEPT EXPLORATION: "VECTORED" RESCUE HOIST

References [1-2] briefly introduced the "Vectored" rescue hoist concept, which was subsequently studied analytically is some detail in [3]. The Vectored rescue hoist is a specialized teleoperated hoist sling/basket-module that would have mounted to it multiple ducted-fan propulsors whose combination of thrust vector lines of action would displace the sling/basket to a substantial lateral offset from an aircraft. The "vectored" teleoperated hoist module would be controlled by the hoist lift operator onboard the aircraft. This would provide the hoist of an additional degree-of-freedom of control and positioning capability that could make a critical difference to pick-up/lift victims that otherwise would not be possible.

(a)



(b)

(c)

Fig. 2a-c – Original (Ref. 1-2) Conceptualization

Figure 3 shows the simple test apparatus used to begin quantifying the static thrust performance of the proof-of-concept ducted fans used for this study. The ducted fan is suspended from the apparatus frame by a pendulum arm (a threaded rod) attached to a pivot. The pendulum arm (from the pivot to the duct outer surface) is 0.90 m. The moment arm (from the pivot to the fan axis) is 1.01 m.

Fig. 3 – Simple Isolated Ducted-Fan Test Stand

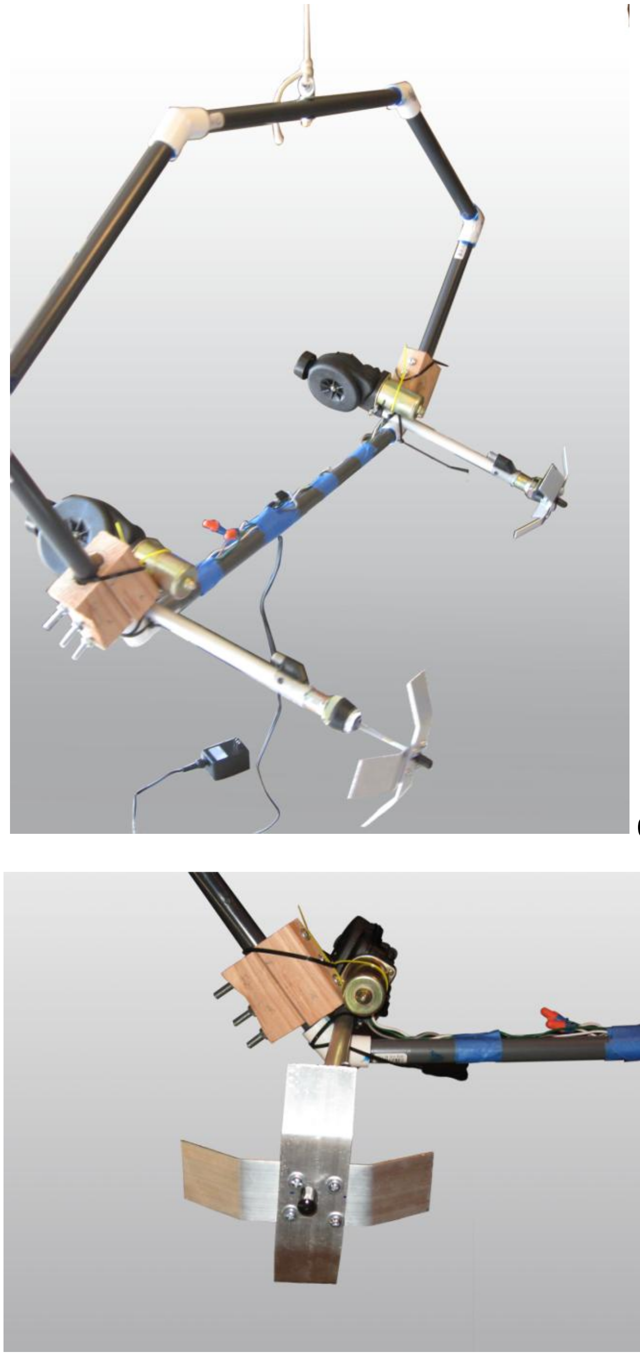
In addition to the isolated ducted-fan static-thrust test stand, a proof-of-concept small-scale dual-ducted-fan hoist test article was also developed. Each test-article/test-stand provided its own valuable insight into the technical challenges underlying the potential development of the Vectored rescue hoist concept. The isolated ducted fan test stand was focused on the question of static thrust performance in light of the necessity to incorporated protective measures, such as inlet and exhaust screens, for the safety in close proximity to fans. The proof-of-concept dual-ducted-fan hoist test article (Fig. 4) was developed to consider some fundamental operational issues underlying the rescue hoist concept. Among theses issues considered, or to be considered, were the issues of how to secure and keep stationary the hoist when fully deployed on-station (i.e. the potential employment of robotic actuators/effectors) and the question of whether the hoist displacement would operationally be effected by steady static thrust or transient/periodic "pumping" of the ducted-fan thrust. The proof-of-concept hoist test article focused on a dual ducted-fan configuration for reasons of simplicity. However, this also is an open issue as to a final operational design for such hoists. More discussion will shortly follow as to the specific work directed towards this initial proof-of-concept effort.

Fig. 4 – Small-scale Proof-of-Concept Test Article

Figure 5 shows more details of the ducted fans used in this study. The two-bladed propellers used in the ducted fan have a 0.21 diameter. They are stock RC airplane propellers that have been modified by truncating and squaring-off of the blade tips. The propeller nondimensional axial location with respect to the duct lip/inlet edge is z/R=0.33; the propeller nondimensional axial location with respect to the duct exhaust edge is z/R=1.90. The propeller "tip gap" is $\Delta r/R=0.07$. The duct sectional-contour is mostly as an uniform flat-plate. The duct has a quasi-linear taper $R_{inlet}/R_{exhaust}= 1.35$; the nonlinearity being most significant at the inlet lip and the exhaust edge. This propeller/duct geometry is non-optimal. For example, the tip gap is comparatively large, Ref 18, and therefore unlikely to generate a significant duct shroud thrust augmentation.

Fig. 5 – Fan & Electric Motor Installation in the Ducts

In order to fully realize the Vectored rescue hoist concept it is necessary to also consider means by which the hoist can temporarily arrest its motion and/or attach itself to fixed structures/surfaces (open office windows, or cliff faces, etc.) in the immediate vicinity of the rescue to be performed. Accordingly, some initial thought was given to the proof-of-concept effort as to possible actuator and effectors that might be used in such a system. This is where the robotic nature of the Vectored hoist is most apparent. A simple "grappling hook" design, mounted to a set of telescoping linear actuators, was incorporated into the proof-of-concept test article (Fig. 6a-b). This arrangement is of very limited functionality in its current form; however, the exercise of attempting to incorporate such actuators into the overall system did provide valuable design and operational insights.



(a) (b)

Fig.6a-b – Actuator and Effector (Grappling-Hook) Proof-of-Concept

Figure 7 is an image of the final form of the hoist proof-of-concept test article. Future work will focus on assessing some fundamental issues related to the control of the hoist lateral displacement as a function of dual-ducted-fan static and transient thrust.

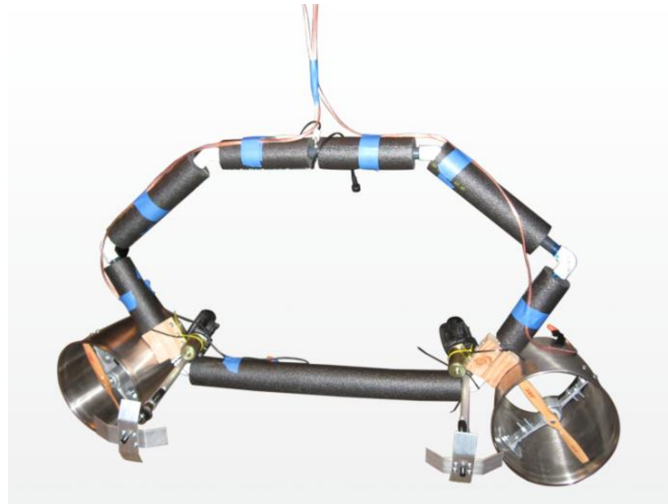
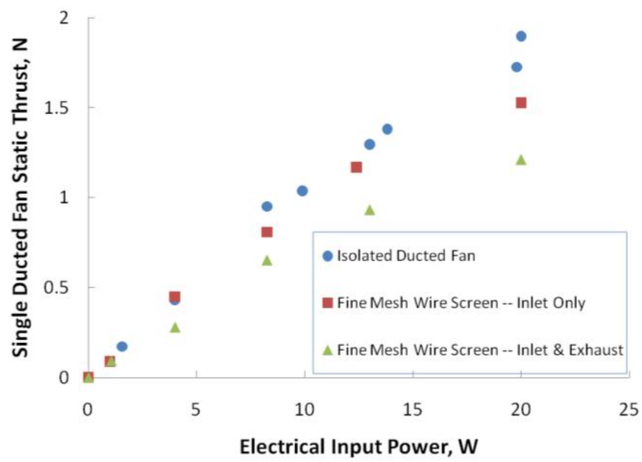


Fig. 7 – Proof-of-Concept Assembly

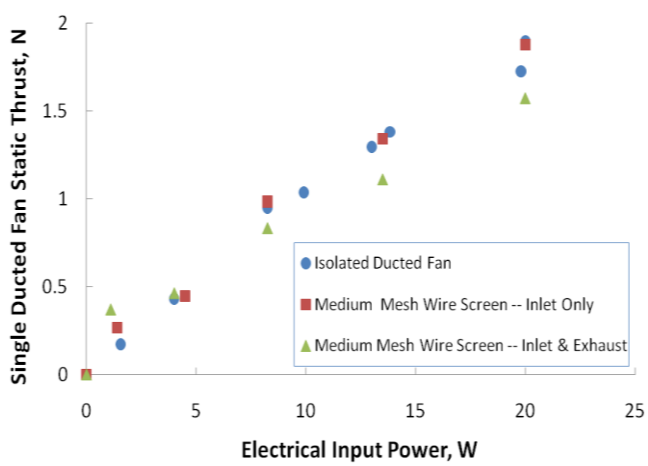
An essential aspect of the "vectored" hoist concept is protecting people from the rotating fan blades of the ducted fans. Accordingly, an exploratory investigation was conducted as to the influence on static thrust performance of the ducted fans due to the addition of protective screens in the inlet and exhaust of the ducts (Fig. 8). Unfortunately, because of the available DC-power supply during this preliminary investigation, the ducted fan could only be powered to only a small fraction of the thrust required for an operational vectored hoist. This power-limitation issue will be addressed in future work.

Fig. 8 – Simple Application of Wire Screens (Large Mesh Screen Shown) to Duct Inlet and Exhaust during Static Thrust Testing

A key preliminary investigation with the static thrust performance test apparatus was to assess the impact of protective wire screens at the inlet and exhaust of the ducted fan. Three different wire mesh screens were used: a "fine" mesh with 3mm even (square) spacing with ~0.4mm diameter round wires; a "medium" wire mesh with 6mm even (square) spacing and ~0.66mm diameter round wires; a "large" mesh with 25.4mm even (square) spacing and 1.5mm round wires. The wire mesh screens for the inlet and exhaust always had the same mesh spacing. Two screen installation configurations were tested for each type of screen (fine, medium, and large): an inlet-only screen installation and an inlet and exhaust set of screens. The screen installations for the static thrust performance testing is very simple in application as can be seen in Fig. 8; no attempt has been made to aerodynamically shape/fair the screens with respect to the duct inlet and exhaust.



(a)



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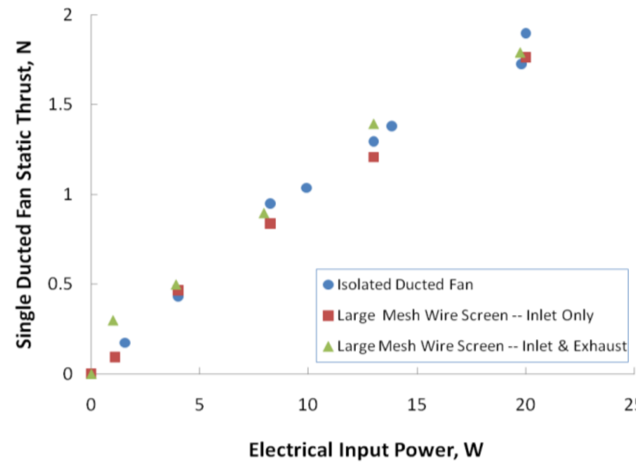
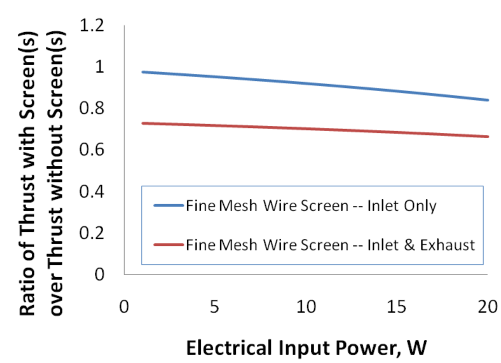


(c)

Fig. 9 – Isolated Ducted-Fan Thrust versus (Input Electrical) Power Trends: (a) Fine Mesh Screens, (b) Medium Mesh Screens, and (c) Large Mesh Screens

There are two contributing factors to the static thrust reduction observed with the use of protective screens for the inlet and exhaust of the ducted fans. First, the parasite drag of the screens themselves that reduce the net thrust of the ducted fan. Second, the fan wake is also likely being adversely modified by the presence of the screens.



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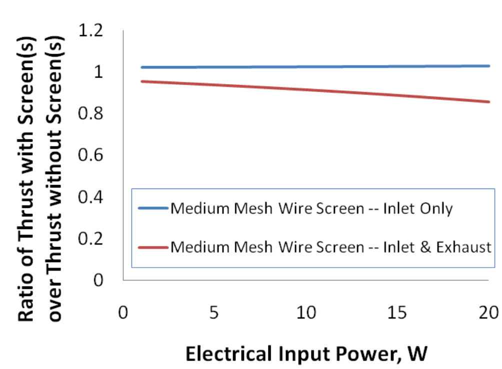

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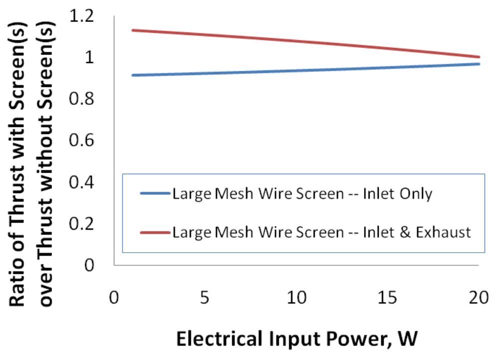


(c)

Fig. 10 – Ducted-Fan Thrust Reduction with Power: (a) Fine Mesh, (b) Medium Mesh, and (c) Large Mesh Screens

The Figs. 9-10 test results can perhaps best be interpreted by considering the static thrust reduction due to screen installation as a function of the collective influence of the screen mesh spacing and the individual wire diameter. In this particular case, the collective influence of mesh spacing and wire size can be assessed in terms of a parameter χ. The parameter χ can be defined such that $\chi = D^2/(n^{2.322} ds + s^2)$ where n is the number of screens, s is the mesh spacing, and d is the wire individual wire diameter. (The constant 2.3219… is defined on the basis that the constant, x, x=2.3219…, is derived from the set of induced-velocity-related equations, those being: (a) $n^x = (1v_i)^2 / v_i^2 = 1$ for n=1 and (b) $n^x = \left((1v_i)^2 + (2v_i)^2\right) / v_i^2 = 1^2 + 2^2 = 5$ for n=2.) Some initial influence of χ on the static thrust performance can be seen in Fig. 11.

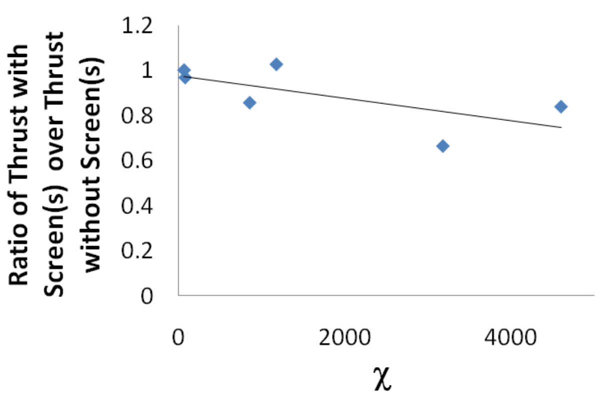
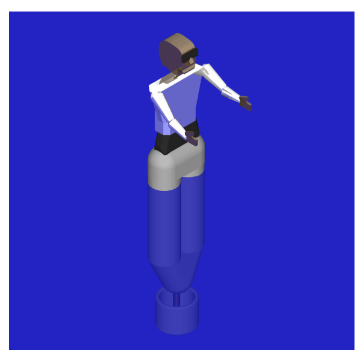


Fig. 11 – Ducted-Fan Thrust Reduction with χ Parameter (data taken at "maximum" (20W) electrical input power)

Figures 9-11, even though only acquired for low static thrust conditions, are suggestive of some simple design guidelines for installation of protective screens for ducted fan vehicles and propulsion systems. First, closely spaced screen meshing should be avoided; coarser spacing is more desirable, even if the individual wire diameter increases. Second, there is probably a net beneficial aerodynamic design tradeoff to increase the length of the duct exhaust (relative to the fan) rather than incorporate protective screening at the exhaust. Third, there is probably an optimal screen mesh/wire-size combination that maximizes personnel protection while minimizing the reduction in ducted fan static thrust. The author is unaware of any theoretical work with respect to fans/rotors operating in hover/static-thrust conditions in close proximity of porous external surfaces, comparable to similar work for nonporous, or solid, ceiling/ground planes such as [24]. This would seem to be interesting, albeit perhaps esoteric, area for future investigation. Finally, wire mesh screens may not be the best means to protect people in close proximity to the fans. Instead, closely spaced stationary vanes are an alternate, perhaps more aerodynamically benign, solution to the problem of personnel protection. This is an area of future research.

IV. Concept Exploration: "Merman" Water Rescue

Reference 1 briefly introduced the "Merman" water rescue robot concept. The "Merman" concept was proposed as an alternative means of effecting high-risk water rescue without unnecessarily jeopardizing military SAR and/or Coast Guard rescue personnel.


(a)

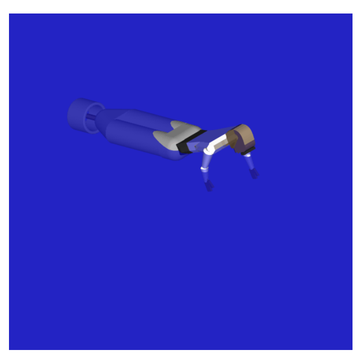

(b)

Fig. 12 – Original (Ref. 1) Conceptualization: (a) upright station-keeping and (b) and in forward motion

Some initial proof-of-concept work was performed in support of defining some of the mechanical system characteristics of the Merman RRD concept. Figure 13 illustrates an early buoyancy test of a partial assembly of a proof-of-concept test article.

Fig. 13 – Partial Assembly Buoyancy Check

The proof-of-concept test article was crafted to also demonstrate one possible out-of-water mobility option for the Merman RRD. Just as aquatic mammals such as seals and sea lions require not only efficient locomotion in the water but reasonable mobility on land, it is anticipated that the Merman system will require a similar capability. This aspect of the Merman concept was not explored in the early references describing the concept. However, the need for some limited out-of-water mobility seems in hindsight to be an important functional requirement that needs to be investigated through prototyping. The approach being taken in the initial proof-of-concept work is the incorporation of a pair of cylindrical rollers at the base of the robotic system. The rollers would have helical treads, with opposing pitch angles, and could be collectively or differentially driven by electric or pneumatic motors. Differential engagement of the motor drive to the rollers would result in steering of the device on the dry surfaces; net forward motion would result from collective engagement/rotation of the rollers. Alternate options for ground mobility could as easily be proposed.

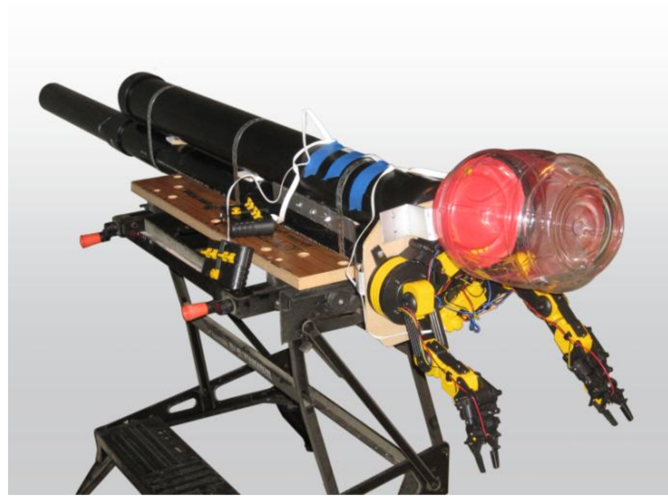


Fig. 14 – Near-Final (Mechanical System) Assembly of the Proof-of-Concept

It is important to consider the human element in any robotic system used in rescue operations. People under difficult, perhaps life-threatening circumstances, will undoubtedly be under considerable strain. A robotic system without some aspect of reassuring sense of humanity will not instill the necessary sense of reassurance and confidence that will be essential for rescue operations. This human-robotic interaction challenge is known as the “Uncanny Valley” hypothesis in the robotics field [21]. It can be addressed, in part, by careful design of the appearance and/or human interface features of the robotic system. For example, in the case of the Merman system, a digital display could be integrated into the system (refer to the transparent bubble at the front of the proof-of-concept test article in Fig. 14 which could accommodate such a display) such that the display could project images of well-crafted reassuring images of cartoon-like features, e.g. the ubiquitous “smiley face,” or even images of the facial features of a young child. Such human-robot interaction issues – which are generally applicable to all RRD applications/systems and not just the Merman and Vectored systems – are beyond the scope of the current work.

It is interesting to note that there are a number of common elements between the “Vectored” rescue hoist and the “Merman” water rescue system. Not the least of which it that both systems require the use of ducted fans/thrusters for their propulsion/mobility. As noted earlier, the necessity of protecting people in close proximity to these systems will require the inherent enhanced safety of shrouded/ducted fans and propellers, versus open-rotor propulsion systems. Further, as briefly explored in a very preliminary sense in this paper, it might be necessary to adopt additional protective measures such as screens and/or vanes for the inlets and/or exhausts.

V. Related Rotorcraft Disaster Relief Investigations

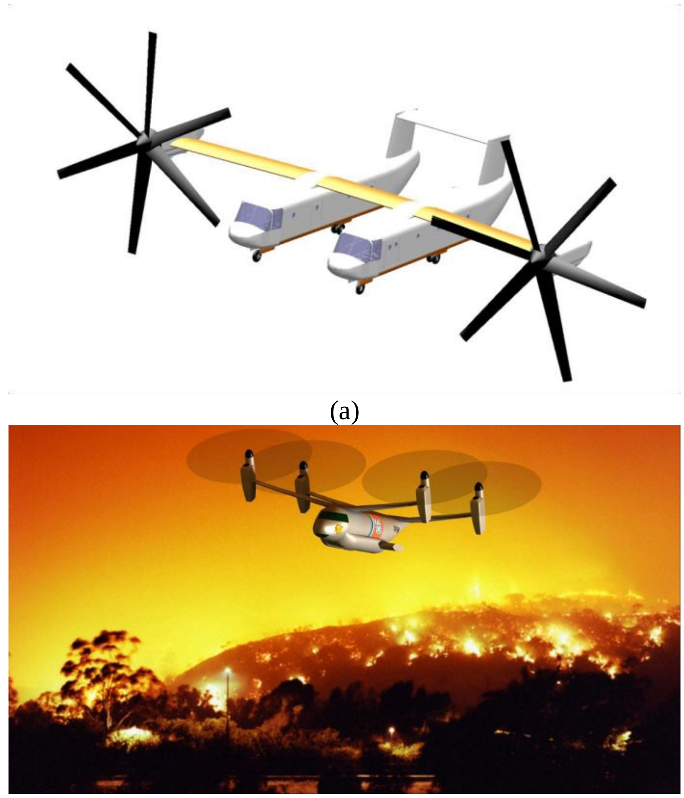
A. Civil Tiltrotor "Civil Reserve Air Fleet" CRAF–Like Disaster Relief Missions

Reference 17 details the ongoing progress towards understanding the technological and operational considerations of operating large civil tiltrotor (CTR) aircraft in the U.S. next-generation airspace system (NextGen). It has long been envisioned by many researchers that CTRs could become a major component of the commercial transport aviation sector. However, the Ref. 17 study proposes to not only examine that facet of the CTR operations in the NextGen airspace but will also seek to equally emphasize the complementary public service nature of these aircraft – the chief component of which is DRER missions.

The Ref. 17 study will seek to use well-established airspace simulation tools, in conjunction with specialized disaster relief operations tools, to assess the impact of a hypothetical CTR fleet performing "Civil Reserve Air Fleet" CRAF–like [19] operations in support of disaster relief missions. The concept of operations will focus on a civilian fleet of tiltrotor aircraft performing day-to-day commercial transport flights until called into action, using CRAF-like operational protocols, to various design relief support roles. Smaller vehicles in the CTR fleet, those that normally performing air-taxi roles or small aircraft operator transport roles, would instead be supporting search and rescue operations whereas the larger vehicles in the fleet would be supporting evacuation and relief supply sorties. The coupled airspace and disaster-relief operation simulation tools will be used to explore CTR fleet responsiveness to various emergency scenarios.

B. Amphibious Tiltrotor for Disaster Relief Student Design Competition

Reference 16 details a recent NASA student competition, for US and international high-school and university student teams respectively, for the design of an amphibious tiltrotor aircraft for disaster relief missions. The objective of the work was to not only inspire innovative vehicle design problem-solving among students but to also to promote innovative thinking towards to societal good goals. It was an unfortunate, but in some ways fortuitous, circumstance that the student design request-for-proposal was issued during approximately the same timeframe as the 2009 Haitian earthquake. This tragic event was, in particular, inspirational to many of the students as regards the potentiality of rotorcraft – especially the amphibious tiltrotor design problem proposed – for disaster relief missions. The students also quickly came to recognition of the fact that many major urban regions are in close proximity to littoral waters, thereby further highlighting the relevance of the design problem posed. Figure 15a-b illustrates some of the proposed vehicle conceptual designs generated by the student competition.



(a)

(b)

Fig. 15 – Some Amphibious Tiltrotor Concepts Stemming from 2010 NASA Student Design Competition: (a) Virginia Tech's Twin-Fuselage/Dual-Hull Design and (b) Georgia Tech's Quad-Tiltrotor Design [16, 20]

VI. Future Work

Future work will focus on developing and refining systems analysis and simulation techniques to better model not only disaster relief response using advanced vertical lift aircraft but rotorcraft-enabled rescue systems. Additionally, proof-of-concept prototype work is anticipated to be continued and expanded to consider other notional robotic rescue device systems. Finally, the two specific proof-of-concept RRD systems discussed in this paper will hopefully continue to be refined into practical systems (Fig. 16). Hopefully, this overall work will help foster collaborative efforts between rotorcraft and intelligent system researchers not only at NASA Ames research center but elsewhere as well.

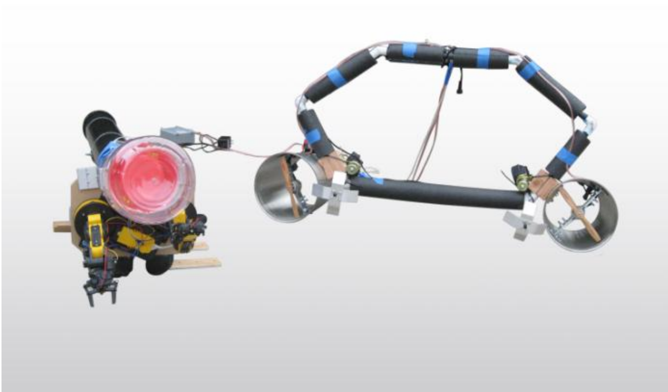


Fig. 16 – Refining, and Defining, New Robotic Rescue Concepts

CONCLUDING REMARKS

Rotorcraft have long been recognized for their role in public service missions, including search and rescue, humanitarian relief, and disaster response, and post-disaster reconstruction. Frequent major DRER missions exert considerable pressure on worldwide resources. To efficiently and effectively conduct future DRER missions, it has been proposed to couple rotorcraft platforms with specialized robotic and intelligent systems tailored to disaster relief and emergency response missions.

This paper summarizes recent efforts related to the potentiality of using rotorcraft for the deployment and control of robotic rescue devices. This paper builds upon earlier work in the area of autonomous systems and vertical lift aircraft for public service missions, especially those related to disaster relief and emergency response.

Finally, some proof-of-concept prototyping work is discussed as related to two robotic rescue device concepts discussed in earlier work: the "Vectored" rescue hoist and the "Merman" water rescue system. These two concepts are merely emblematic of what is proposed as a whole new class of rotorcraft-enabled DRER related autonomous and robotic rescue systems.

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