Small Autonomous Air/Sea System Concepts for Coast Guard Missions

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A number of small autonomous air/sea system concepts are outlined in this paper that support and enhance U.S. Coast Guard missions. These concepts draw significantly upon technology investments made by NASA in the area of uninhabited aerial vehicles and robotic/intelligent systems. Such concepts should be considered notional elements of a greater as-yet-not-defined robotic system-of-systems designed to enable unparalleled maritime safety and security.

I. Introduction

SMALL autonomous air/sea systems can potentially have a revolutionary influence on maritime safety and security. It is only through a measured application of autonomous system technology, air/sea platforms, and small mobile robotic systems can the critical, yet daunting, effort of securing our Nation's waterways and ports be mitigated to a manageable sustainable level in terms of resources required (particularly human resources). With the substantial homeland security demands placed upon the U.S. Coast Guard (USCG)[1] there is a clear need to examine how autonomous system technology can contribute to USCG missions. NASA Ames Research Center has for several years conducted research and development efforts into uninhabited aerial vehicles (UAV) and intelligent systems[2-5]. This NASA technology expertise and system development experience is directly pertinent to emerging USCG requirements. In particular, manned and unmanned aviation assets, coupled with robotic systems such as UGVs (unmanned ground vehicles), USVs (unmanned surface vehicles), and AUVs (autonomous underwater vehicles) and other intelligent devices, provide a powerful means to project maritime domain awareness and, as need be, force. But, it is not the individual platform or system that will make the crucial difference in maritime safety and security, instead it is the combined synergistic effect of several systems having diverse but coordinated elements that will provide the needed utility/mission-capability for the future.

The realization of this vision of a maritime robotic system-of-systems as actual operational hardware will entail nurturing modest R&D efforts unique to the maritime/Coast Guard mission. Otherwise, most of the undertaking will result from a natural progression of current technology trends (such as the DOD network-centric warfare concept and similar technologies to be incorporated into the USCG "Deepwater" project). Additionally, in certain specific cases, complementary research and development efforts currently underway in diverse fields such as UAV technology, in-space robotics, and planetary-surface robots will also be enablers.

Table 1 summarizes the specific notional system concepts, and their anticipated capabilities, discussed in this paper. These concepts are rather whimsically named "Interface," "fractal flyer, "bilge rats," and the "Merman" and "Vectored" robotic rescue devices/hoists. In particular, these concepts seek to address five areas of the USCG mission: interdiction, security surveillance, contraband inspection, civil search and rescue (SAR), and maritime safety. Not unexpectedly, because of the NASA Ames heritage expertise in rotary-wing vehicles, two of the concepts noted in Table 1 support helicopter civil SAR missions.

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Table 1. Systems and Missions – A Few Notional Concepts

Mission	Systems	New Capabilities
Interdiction	"Interface"	Airdrop (from a manned aircraft or UAV) and deployment of small robotic pursuit or surveillance craft (USV or AUV). The aviation asset provides the range and speed to close with suspicious marine craft; the air-deployed USV/AUV asset provides for both close-in and, as need, covert operations.
Security Surveillance	"Interface"	See above. Additionally, as a unique wrinkle on things, the airdropped USV or AUV asset could deploy on need a micro air vehicle for unprecedented aerial inspection of suspicious maritime activity.
	Fractal Flyer	A hybrid, expendable, rapid response UAV concept wherein good long range and endurance characteristics are preserved in the vehicle "collective" cruise configuration. Upon reaching the site or survey area of interest the vehicle would physically separate in-flight into a swarm of smaller low-altitude/short duration fliers.
Contraband Inspection	"Bilge Rats"	Small UGV robots (teleoperated) that would be deployed onboard suspicious marine craft for passenger/cargo inspection. The deployment could be carried out in a number ways: e.g. hand-carried onboard by USCG personnel or even airdropped. The small robots would have sensors and mobility capability sufficient to access otherwise impractical areas to inspect. The UGV robotic assets could be recovered upon the vessel reaching port.
Search and Rescue	"Merman" Robotic Rescue	A robotic rescue device that would assist/aid USCG SAR rescue swimmers. Derived in part by advances in teleoperated robotics, and autonomous watercraft and submersibles, this robotic rescue device provides a safe alternative for rescue of victims in hazardous sea states.
	"Vectored" Rescue Hoist	A rescue hoist module whose free-end possesses propulsors (ducted-fans) to provide enhanced precision and access to victims. The teleoperated propulsor module would be used to even fly outside the footprint of the helicopter rotor disk and, with rescuee-recovered guidelines on the propulsor module, could be used to rappel down and over to a more optimal lift position for the helicopter hoist.
Maritime Safety	Fractal Flyer	See above. This hybrid UAV concept provides a potentially swifter approach as compared to current methods for surveying maritime areas of interest.
	"Interface"	Large vessel outer-hull damage inspection by airdropped micro-submarine or submersible for characterizing magnitude of fuel/chemical spills and/or general sea-worthiness.

Each of these concepts will be discussed in more detail in the following sections of this paper. Note, finally, for many of these small autonomous system concepts there is a common issue as to robotic asset recovery (or lack thereof, if the system is considered expendable) upon completion of the mission. This will also be discussed, as appropriate, later in the paper.

II. "Interface" – A New Multi-Platform Air/Sea Paradigm

The "Interface" moniker for the aforesaid concept alludes to efficiently plying, in fact taking the fullest operational advantage of, the maritime air/sea interface (that zone of operation a couple of hundred feet above and below the water's surface) in pursuit of USCG missions. In this manner, stealth, persistence, and, at times, bursts of unexpected speed in response to need can be best effected. The notional "Interface" system encompasses three conceptual elements: 1. an airdropped micro-submarine (a.k.a. AUV) for "stealth" ship tracking – inspired, as it were, by WWII torpedo bombers and modern-day anti-submarine warfare aircraft; 2. airdropped high-speed micro-hydrofoil pursuit/intercept USV; 3. surface-launched rotary- or fixed-wing micro air vehicles (MAVs) from micro-submarines for close shipboard inspection and potential-violation-documentation.

Figure 1 illustrates the notional airdrop of a micro-submarine payload from a fixed-wing UAV. Note the low-drag nature of the micro-sub with its folded/fanned-back diving-planes/lifting-surfaces during UAV air-transport. These surfaces could act as snorkel masts (if deployed near-vertically above the water) for air-breathing propulsion underwater, if need be. Alternatively, they could act as conventional dive-planes/stabilizers. And, upon completion of its primary mission, the micro-sub lifting surfaces could convert configuration-wise into an unpowered underwater glider[6] to return to a safe recovery zone. A considerable body of research has already been conducted into AUV and underwater glider technologies by various research organizations. What is needed, in addition to this ongoing work, is examination of those technical issues related specifically to the airdrop from UAVs or manned aircraft for such vehicles. This in turn touches upon specific aerodynamic/hydrodynamic vehicle-configuration design issues, as well as innovative variable-geometry/actuator concepts.

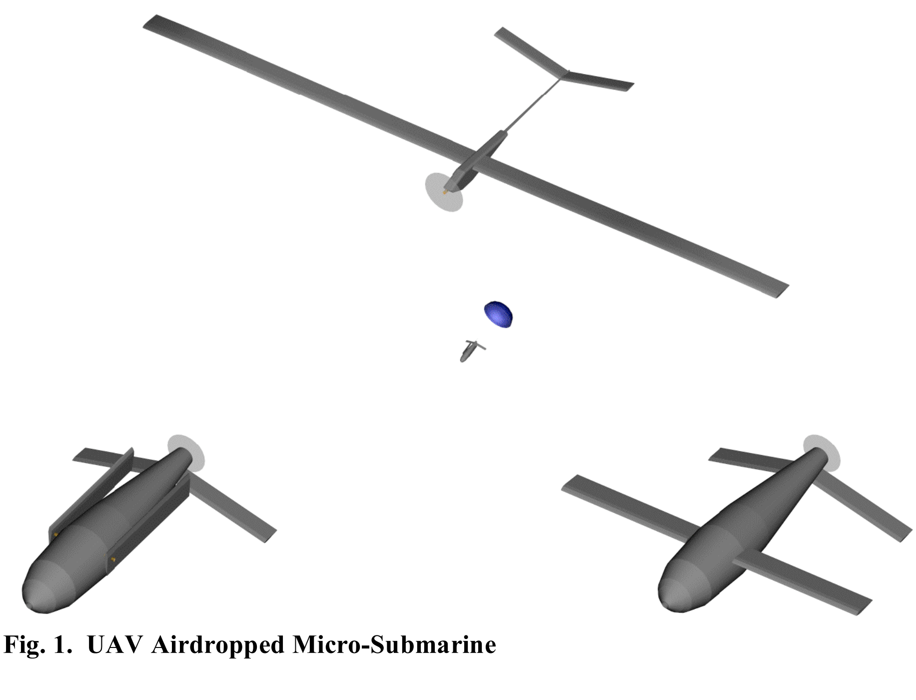
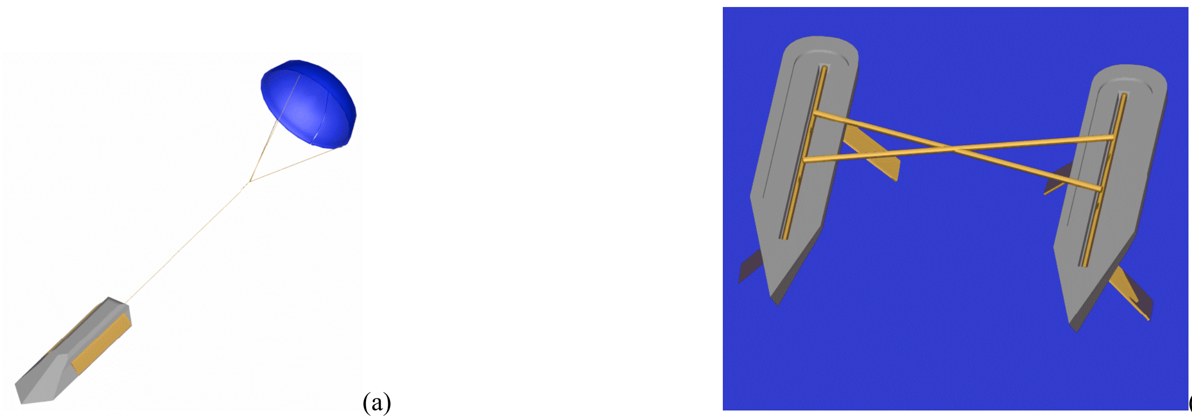


Fig. 1. UAV Airdropped Micro-Submarine

Figure 2a-b is an illustration of an airdropped micro-hydrofoil USV concept. The USV, when deployed on the ocean's surface, would act as a high-speed pursuit/interceptor asset. The ideal goal of such a USV interceptor would be to have an acceleration and speed unmatched by any manned high-speed watercraft. Figure 2a shows the USV in its stowed airdropped form (with its catamaran twin hulls mirrored/mated closely together to form a low-drag streamlined shape for UAV air-transport). A drogue parachute stabilizes the airdropped payload during its descent.

Figure 2b shows the notional catamaran micro-hydrofoil interceptor in its fully deployed configuration (as it speeds along the surface of the water).

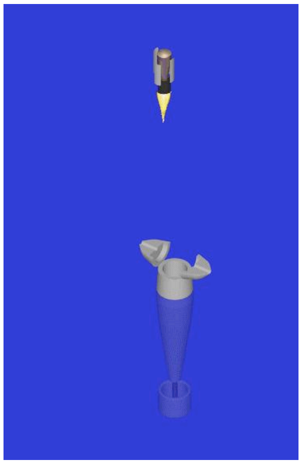
Though there is a substantial body of work related to high-speed hydrofoil design already available in the technical literature, there are clearly many issues that would need to be addressed for the type of airdropped micro-hydrofoil proposed herein. Among those technical issues are: 1. configuration design trades to accommodate stowing a vehicle in a UAV air-transported state, 2. complex mechanical systems and actuators to effect the transformation of the vehicle from a stowed state to a deployed sea-ready cruise state, and 3. automation, control-law, and vehicle dynamics issues that would need to be resolved to allow for fully autonomous high-speed operation on open water.



(a) (b)

Fig. 2. Airdropped High-Speed Micro-Hydrofoil USV Interceptor: (a) air-dropped and (b) deployed

Figure 3a-b depicts the notional (ballistic) surface-launch and subsequent flight of a coaxial rotary-wing micro air vehicle[2] from a micro-submarine. Such a micro air vehicle adjunct to USV and AUV assets would be a powerful tool for enhanced close-in covert surveillance of suspicious maritime activity. For example, the USV or AUV carrier-craft could discretely shadow a suspicious surface vessel for an extended period of time and, at some critical juncture/time (such as surreptitious unloading/loading of cargo mid-ocean), a MAV would be launched from the carrier-craft. The MAV would then convert into a forward-flight configuration for detailed imaging/documentation of the suspicious event. It is anticipated, in such a scenario, that such sea-launched MAV would likely be expendable.


(a)

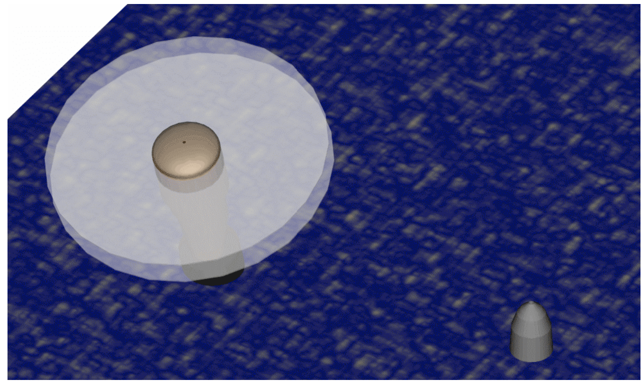

(b)

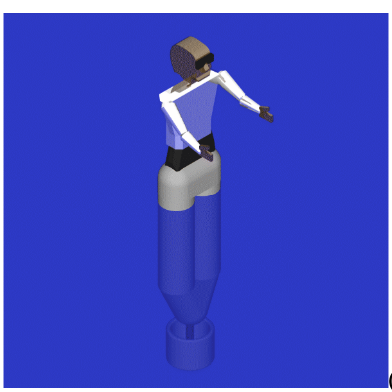
Fig. 3. Surface/Sea-launched (from Micro-Sub) Micro Air Vehicles

There are many unique technical challenges for developing such a MAV sea-launch capability. Among those challenges are the ballistic launcher characteristics, the design robustness of the MAV under inertial loads during launch, and the mechanical/flight-dynamics issues inherent in the mid-air conversion of the MAV configuration from a stowed ballistic package to a flyable aerial asset.

III. "Merman" Robotic Rescue Device

The "Merman concept builds upon NASA robotics expertise such as that developed for the teleoperated/semi-autonomous NASA Robonaut[7,8]. The Merman is intended to be one part life raft, one part rescue hoist, and one part rescue-swimmer. This Robonaut-like device (in that both have anthropomorphic upper torsos) would replace and/or enhance rescue-swimmer capabilities in extremely hazardous sea-states and emergency conditions -- refer to Fig. 4a-b. The "Merman" robotic rescue device could be operated tethered (to a helicopter rescue hoist) or operated freely untethered with independent propulsor capability.

The Merman device would have the capability of reaching (via its propulsors) and rendering assistance to (via its robotic arms and overall positive buoyancy) victims in the water. Upon reaching them in the water, the device would ultimately place victims into standalone hoists and rescue baskets for recovery. The Merman device could either be teleoperated by human operators onboard the rescue helicopter, from a C-130 aircraft circling over the rescue site, or from ground stations on the shore.


(a)

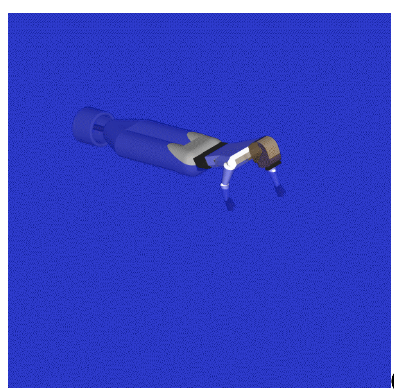

(b)

Fig. 4. Helicopter Hoist-Deployed Robotic Rescue Device: (a) upright station-keeping and (b) and in motion

Though oceanographic submersibles have long employed robotic arms and other effectors to retrieve materials and organisms from the sea floor, and perform other tasks underwater, trying to meld anthropomorphic robotic systems with marine system hardware components has not been performed to date.

IV. "Vectored" Rescue Hoist

Continuing with the theme of robotically augmented SAR equipment, Fig. 5 illustrates the "Vectored" rescue hoist concept. Conventional helicopter rescue hoists significantly limit operational flexibility to performing lifts in relatively obstacle free environments directly below the rotor disk "footprint" of the helicopter. To attempt otherwise is to run the risk of snagging the hoist cable on intervening obstacles or even, in certain cases, risking blade strike with large superstructures or coastline cliffs and other rock formations the helicopter may be flying alongside. What is required is an additional element of control (beyond that afforded by the pilot station keeping with the helicopter) in terms of positioning the hoist sling/basket -- both in terms of precision and overall magnitude of lateral/radial displacement from directly underneath the helicopter. This enhanced control of the hoist "free end" would be effected by 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 the required offset from the aircraft. The "Vectored" teleoperated hoist module would be controlled by the hoist lift operator onboard the aircraft.

The "Vectored" hoist module would have enough ducted-fan propulsor thrust capability to move an unloaded sling/basket into a needed lateral position for rescue -- but not when carrying a victim. Therefore, it is anticipated that the "Vectored" rescue hoist module would also be outfitted with a reel of guideline that would be secured by rescuees to allow motorized "rappelling." This motorized guideline would then be used to move the hoist sling/basket (with victim) downward and sideward along a diagonal line -- from an otherwise inaccessible pickup

Fig. 5. "Vectored" Rescue Hoist Module Suspended from Helicopter: Reaching the Previously Unreachable

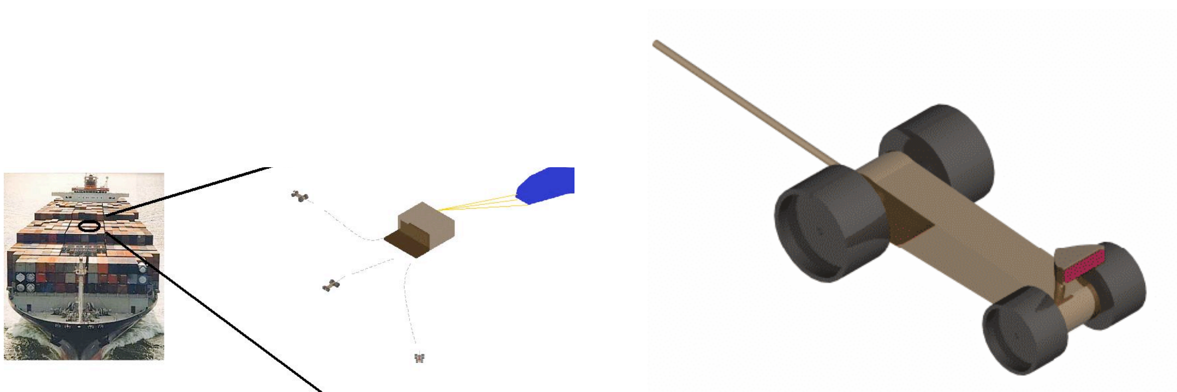
location the helicopter couldn't fly alongside or over – to position it directly underneath the helicopter for optimum lifting once clear of hazardous obstacles.

V. “Bilge Rat” Boarding Inspection/Surveillance System

Figure 6 shows the notional attributes of the “bilge rat” concept – a UGV robotic asset tailored for the unique demands of at-sea shipboard inspections. Among the unique operating requirements of such a device is operation near or in saltwater, or other shipboard fluids/solvents, and acceptable mobility in very tight confines with poor surface traction and extremely challenging access/egress points such as bulkheads, doorways, steerage hatches, and stairways/ladders. Having said all of that, the mission-capability promised by the “bilge rat’ concept could represent a quantum-leap in terms of contraband inspection on the high-sea, well before port is made.

Such a shipboard micro-UGV capability for contraband inspection is not unlike certain ongoing DOD robotic research efforts in support of urban warfare and insurgency suppression – safe scouting/surveillance by small man-portable robots inside buildings or other enclosed structures[9,10]. NASA expertise in rovers and micro-rovers is also directly applicable to the development of such shipboard inspection robots. Satellite networks makes communication to/from the “bilge rats” at sea by operators on shore feasible.

The “bilge rats” could be carried onboard by USCG crew boarding a vessel at sea to be inspected, or could even in the most extreme cases be airdropped onboard. Such inspections could theoretically last the whole of a vessel’s voyage, i.e. the “bilge rats” could do continuous monitoring until the vessel reaches port and then be recovered. This extended period of inspection and enhanced access to shipboard cargo and working areas would greatly increase the probability of discovering contraband or illicit onboard activities. Access to U.S ports might denied to the vessel, if the bilge rats were not allowed free reign. Patterns of subterfuge or denial of access to certain areas at certain times by the crew to the “bilge rat” robotic inspectors could be analyzed/assessed by USCG staff and port authorities as being warning flags for more detailed inspection in port by human inspectors.



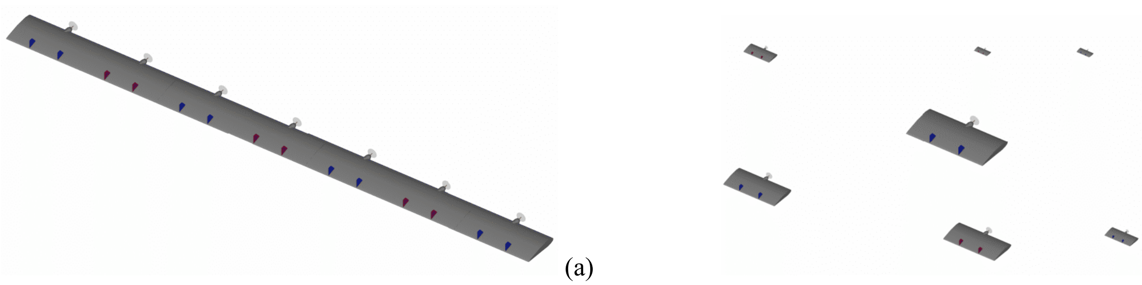
(a) (b)

Fig. 6. (a) “Rats” Being Airdropped Onboard and Scurrying through the Ship in Search of Contraband and (b) close-up image of a “rat”

VI. Fractal-Flyer

The “fractal flyer” concept seeks to address one of the major limitations of small autonomous aerial vehicles: i.e. how to provide for adequate endurance and range while at the same time effecting missions that emphasize the small size and large numbers of aerial assets[2]. Figure 8 illustrates the key features of the “fractal flyer” UAV concept. It is a hybrid configuration in the context that it is multiform in nature. When it is in cruise configuration it is optimized in form for long range and endurance – i.e. its overall planform is that of a large span, large aspect ratio, flying wing. When it is in search mode, the vehicle physically separates (by mechanically detaching at “wing-tip” attach points/joints for individual flyer elements) into a swarm of smaller, low aspect ratio fliers performing low-altitude searches. The “fractal flyer” concept is similar in nature to the “parasite fighter” concept investigated in the earlier half of the twentieth century. However, by focussing on small lightweight UAVs, the flight loads on the wing-tip attach points/joints of the individual “fractal flyer” elements should be more tractable than that for larger (manned) aircraft, as was previously studied in the parasite fighter concept.

The “fractal flyer,” in general, is an expendable asset. Once the vehicle separates into multiple individual fliers they will likely have insufficient range (upon completion of a search) to make it back to a recovery site. However for high-value, rapid response emergencies covering large search areas, the “fractal flyer” concept potentially represents a new paradigm in search and recovery assets.



(a) (b)

Fig. 8. Fractal-Flyer: (a) cruise (collective) configuration and (b) resultant swarm of individual fliers

VII. Concluding Remarks

A number of small autonomous system concepts have been examined in the context of one day potentially supporting USCG missions. These concepts build off of ongoing work within NASA and elsewhere in the areas of uninhabited aerial vehicles and robotic/intelligent systems. In this regards these concepts (and their inherent technologies) represent a good starting point for nurturing cooperative “public good” research in the area of maritime safety and security.

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