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Design Considerations for Autonomous Launch and Recovery of Unmanned Surface Craft

ABSTRACT

The accomplishment of launch and recovery of Unmanned Surface Vehicles (USVs) at sea poses new and unique technology development challenges. USV, USV host ship, and USV/host ship interface equipment design are simultaneously evolving and require specialized interfaces. The approach taken to solve these challenges influences the design of both USV and host ship and creates a new category of equipment. The development of technology that addresses the most difficult of these challenges is subject to a wide band of design and development process considerations for the sake of compatibility with the USV and host ship. Coupled with these challenges is the need for a high level of craft control and equipment reliability to mitigate risk of damage from at-sea docking. Autonomous launch and recovery systems under development should all meet the same general set of safety, reliability and performance criteria and minimize impact to both the USV and host ship. This paper identifies some of the unique operational conditions that exist when trying to recover USVs and proposes a set of general launch and recovery considerations based upon current at-sea testing being performed by Naval Surface Warfare Center Carderock Division (NSWC CD), Code 23. The goal of this paper will be to provide an autonomous launch and recovery baseline and make recommendations for future USV autonomous launch and recovery development. Lessons learned will influence future designers by providing a more balanced perspective about autonomous USV launch and recovery technology development considerations. This paper is based on technology development work at Naval Surface Warfare Carderock Division, Code 23 sponsored by the ONR (Code 33) Unmanned Sea Surface Vehicle program.

INTRODUCTION

Autonomous launch and recovery of Unmanned Surface Vehicles (USVs) at sea is an emerging hybrid naval technology. Launching and recovering boats and craft from larger ships is not a new concept, but the requirement to recover USVs has created some new technical challenges that are driving designers to synthesize and develop a new category of recovery methods and equipment. The primary function of an autonomous launch and recovery system is simple; enable a USV to be brought aboard a host ship safely, efficiently, and without damage to either the USV or host ship in the intended operational environment and in a reasonable time period. The operational environment involves extreme salt water exposure, dynamic conditions that are not well defined, and with two large floating objects that are intended to have a controlled collision, or recovery. Beyond this, PEO SHIPS (Hamilton,2005) has identified several launch and recovery operational design objectives:

- Need launch and recovery systems that require few or no people to operate
- Need launch and recovery systems that require reduced time to execute launch and recovery (tactical speed)
- Need launch and recovery systems that are flexible enough to accommodate a wide variety of vehicles over a period of time

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14. ABSTRACT
The accomplishment of Launch and Recovery of Unmanned Surface Vehicles (USVs)at sea poses new and unique technology development challenges. USV, USV host ship, and USV/host ship interface equipment design are simultaneously evolving and require specialized interfaces. The approach taken to solve these challenges influences the design of both USV and host ship and creates a new category of equipment. The development of technology that addresses the most difficult of these challenges is subject to a wide band of design and development process considerations for the sake of compatibility with USV and host ship. Coupled with these challenges is the need for a high level of craft control and equipment reliability to mitigate risk of damage from at-sea docking. Autonomous Launch and Recovery systems under development should all meet the same general set of safety, reliability and performance criteria and minimize impact to both USV and host ship. This paper identifies some of the unique operational conditions that exist when trying to recover USVs and proposes a set of general Launch and Recovery considerations based upon current at-sea testing being performed by Naval Surface Warfare Center Carderock Division(NSWC CD), Code 23. The goal of this paper will be to provide an Autonomous Launch and Recovery baseline and make recommendations for future USV Autonomous Launch and Recovery development. Lessons learned will influence future designers by providing a more balanced perspective about Autonomous USV Launch and Recovery technology development considerations. This paper is based on technology development work at Naval Surface Warfare Carderock Division, Code 23 funded by the ONR(Code 33)Unmanned Sea Surface Vehicle program.

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- Need platforms to create enough stability in motions to facilitate launch and recovery (sea keeping/human factors)

- Need platforms and launch and recovery systems to be modularized

The objectives are clear and concise. However, the realization of these objectives involves USV integration, host ship integration and concept comparison and evaluation issues that make the design target less well defined and involve substantial engineering design judgment, often by different engineers or engineering entities. As integrations and optimizations between recovery equipment and host ship or USV occur, co-dependencies are frequently created between components that must be uncoupled to accommodate late gross arrangement changes. This makes post design changes complex and expensive, underscoring the need for early equipment design integration with the USV and host ship. Some of these objectives have been achieved in recent Naval Surface Warfare Center, Carderock Division (NSWC CD) Code 23 efforts for development of autonomous launch and recovery equipment for use in the current LCS concepts of recovery for ONR.

There have been several efforts to synthesize and develop concepts for launch and recovery of boats and craft (Surface Combatant Optimized for Unmanned Vehicles,12 December 2002) (Sheinberg, R. et al 2003) and autonomous launch and recovery (Eisenberg 2005) (Coats 2006). Leadership recognizes that the successful operation of USVs is dependent on the capability of delivering and recovering the USV from the operational area (PEO MLW & OPNAV, July 2007, p 78). The parallel exploration of many concepts (and the need to convey comparative operational suitability to leadership) has created a need for base-lining some of the primary design considerations associated with developing these concepts and equipment. This paper will present design considerations for an autonomous launch and recovery system based on the current NSWC CD Code 23 effort to develop equipment in this category. Presentation of autonomous launch and recovery design considerations will occur in three parts; first with load transition equipment on the USV; then considerations for the launch and recovery equipment, and finally considerations associated with load transition to the host ship. One goal of this paper is to help characterize and refine these issues to allow quick identification of concepts with realistic expectations about fleet integration success and elimination of concepts that are novel and unproven. Although autonomous launch and recovery are typically thought of as a matched pair of operations, by far the most complex aspect of the process is the recovery process, and by far the most challenging aspect of the recovery process is the initial connection between USV and host ship. As a result of this challenge, the focus of this effort will be on recovery.

The methods by which the two current LCS designs recover USVs are vastly different and will not be discussed in this paper due to the on-going competition between contractors. This paper will identify as many design considerations as possible and provide some insight into how the prototype USV latch mechanisms developed by NSWC CD Code 23 were engineered to meet these challenges. Many of these considerations will be applicable to any recovery system interface between a USV and a host ship.

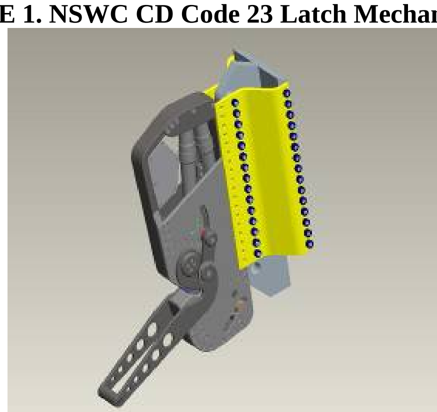
BACKGROUND

The focus of the most recent NSWC CD Code 23 and ONR latch development was to fill the technology void between USVs and LCS identified recovery methods. This led to the development and testing of an initial prototype tow body/latch system in 2004-2007. Despite its operational success, the initial prototype had several features which made it undesirable to USV designers looking to integrate it into USV designs, chiefly its size. However the initial prototype clearly demonstrated that a line could be caught and released automatically from a towed body and was compatible with the line presentation methods for both LCS concepts of USV recovery.

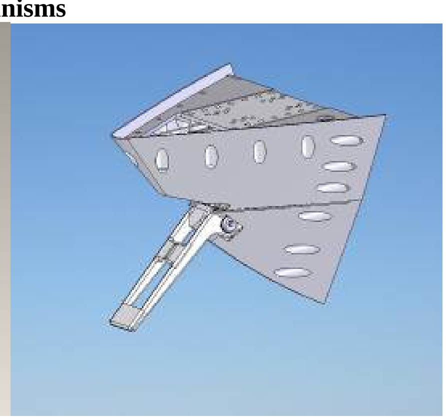
Integration of the latch design into USVs became the mantra of the FY07 NSWC CD C23/ONR design effort. The integration challenge was actually two-fold as there would be instances where a USV design lent itself to full integration of the latch mechanism, and instances where a USV design precluded full integration of the mechanism into the hull design. The second-generation designs would have to minimize weight and hydrodynamic impacts, while still maintaining a high percentage of capture. The goal was to produce a tested developmental prototype that could be easily and rapidly transitioned to production equipment. In addition to the USV integration constraints, both prototype latch mechanisms would need to work with each LCS concept.

Again, skirting the design of different recovery methods used by both current LCS concepts, the common interface became a line presented to the USV at or slightly off the water, just off the stern of an LCS in a horizontal configuration. Latch mechanisms grapple this line using a horizontally oriented 'V' shaped guide, with the force of the USV momentum being enough to cause latching to occur (Figure 1). These mechanisms were fabricated (NAVSEA DWGS 5108440 &5108441) and tested using the High Tow Force Unmanned Sea Surface Vehicle (HTF USSV) during FY 07 (NSWC-CD-TM-2007/31 & 2007/32).

FIGURE 1. NSWC CD Code 23 Latch Mechanisms



External Design



Internal Design

CONCEPT OF OPERATIONS IN AUTONOMOUS RECOVERY

The recovery process starts with a USV returning from a mission. The first stage of recovery involves getting the USV into recovery position successfully using autonomous sensors and a control system to enable connection with the host ship. The exact parameters of this capability are a function of USV steering at recovery speed, USV control system, and the self-aligning capabilities of the recovery system being employed. Such control systems exist and have been demonstrated (Web et al 2005). Once the USV is in position, connection of some kind can occur between USV and host ship, gradually transitioning control of the USV to the host ship. This initial connection can come in many forms, such as ramps, towed components, and snaring/lifting davits or cranes, each with different transitioning rates and sensitivities to environmental conditions. The USV recovery process can be thought of as a process which gradually compels two independently moving craft to eventually move as one, which occurs when the USV is aboard the host ship.

USV AUTONOMOUS LAUNCH AND RECOVERY DESIGN CONSIDERATIONS

As they become more integrated into the operational plans of war fighters, USVs will be asked to do more and likely become larger with designs being further optimized for mission payload, speed or fuel capacity. This expected growth means additional design competition for space and highlights the need for an awareness of the weight and geometry issues faced by USV designers.

USV INTERFACE WEIGHT DESIGN CONSIDERATIONS

Any launch and recovery device will add weight to a USV, but how much weight and where it is positioned are somewhat controllable factors. Weight has a two-fold detrimental impact on USVs as they are engineered for extreme performance and typically are weight sensitive. Every pound of added weight for launch and recovery equipment comes at the expense of payload or fuel, resulting in a reduced mission capability or range of operations. Weight added all in one location (such as the bow) has the capacity to change the trim and handling characteristics of the USV. In short, the addition of weight to USVs reduces their capability and may intensify stability problems.

Knowledge of USV weight sensitivity concerns made one objective of the FY07 ONR latch design effort a reduction in weight from the initial prototype device weight of 170 lbs. After discussion with USV project managers, the initial design weight target for the new latch devices added to the USV was 100 lbs. The 100 lb device weight was achieved in an aluminum version of the external design, with a device weight of 94 lbs. In addition to the mechanism, structural modifications to the bow and adapter plates are needed for load transition to hull structure. Weight attributed to the internal design mechanism and the transition structure is less well defined for the internal mechanism. In this design there were structural modifications made to the USV, adding plate and structure to the hull and cover plates for a removable bow section containing the latch mechanism. The latch mechanism weighed about the same as the external design. It should also be noted that integration of an internal latch design should include considerations of accessibility for service and maintenance. The weights of prototype devices are listed in Table 1.

TABLE 1. Comparative Weights of Launch and Recovery Design Prototypes

Device Style	Component	Weight (lbs)
Original Prototype	Device	170
	Side plates & hardware	100
	Total	**270**
External	Device	94
	Transition Plates	73
	Total	**167**
Internal	Removable Bow Section	75* (not included in total)
	Latch Mechanism	99
	Added USV Structure/Bolts	66
	Total	**165**

USV GEOMETRY DESIGN CONSIDERATIONS

USV geometry changes are predictable as weight changes. The most obvious geometry issue is the potential increase in USV length. As minor as this sounds, an increase in length impacts ship storage and handling, trailering, and potentially air cargo capabilities of the USV. Trailering in particular has some additional issues as the device can cause the trailer made for the USV to no longer be the right length, foul the trailer winch, and prevent the USV bow eye from being accessible for a trailer tow winch pull. The foul may occur anywhere during the launch or recovery transition from trailer to water. Only totally retractable designs would be immune to this issue.

For designs such as the latch concepts developed, forward protrusions also create a potential foul and snagging concern, particularly since they are right at the waterline. In littoral waters where crab pots, fish lines or submerged obstructions are likely, the device could easily be damaged from a waterborne impact or an impact that occurs as the result of a recovery or docking evolution. This risk is reduced somewhat by having a retractable stored position, removable device and the realization that when the devices are in recovery position they will be following in the path of the host ship. However, it is incumbent upon the launch and recovery equipment designer to accommodate these perils. The relative size of the USV makes the even small impacts substantial if impact occurs with a protruding recovery device. USV and launch and recovery equipment designers need to plan the integration of the recovery device into the USV such that large forces exerted on the bow by snagging something at a high speed do not cause extreme damage to or loss of the USV.

A protrusion also presents a potential hazard to the ship during the final phases of recovery. In addition to damaging the USV recovery mechanism, an unexpected combination of wave induced boat/ship motions could cause a protrusion to damage or entangle bunking or shipboard recovery equipment. A protrusion can foul other shipboard recovery devices, such as nets or sponsons, hit ramps or trailers as the boat is being launched, and take unwanted loads during crane lifting evolutions. In addition to the potential damage to what is hit, there is the potential for damage to the recovery device itself. A design feature employed by the prototype latch mechanisms to avoid this concern is a lower guide that is retractable after connection with the host ship. The only thing that can be done to reduce the impact of the external design latch mechanism geometry is to make the housing and transition as conformal to the existing hull of the USV as possible and control the ability of the forward most surface to take an impact. For the internal style however, the mechanism can be made retractable to varying degrees, but there is a design trade-off that involves increased complexity and corresponding loss in the forward most space inside a USV. As a point of reference, the internal style mechanism had an aft boundary of the USV’s collision bulkhead. This design measure seems a prudent design consideration for other similarly mounted devices. Also involved in this trade-off is cutting some type of opening into the bow of a USV for access to the equipment once installed. In keeping with the PEO SHIPS call for modularity in launch and recovery systems design, a design innovation conceived for adaptation of the internal mechanism into the MIW USV design was a removable bow section that enables swapping of latch mechanisms or total removal of mechanisms, depending on mission.

Although the overarching focus of the bow mounted latch mechanisms was compatibility with current LCS recovery methods, other geometries for recovery are possible. One discussed method involved removing the connection point from the bow of the USV, favoring instead a top mounted recovery location. Topside locations offer the advantages of reduced drag on hull relative to designs with protrusions, reduced corrosion and maintenance issues for the same reason, and removing the connection device from a potential impact area. However, if connection involved towing the USV, there would be a loss in towing stability resulting from a higher tow point. A second concept being pursued in a parallel effort by ONR is a probe/receiver/sponson connection method. This concept has only a cylindrical probe on the bow of the USV with the receiver supported by some other means, such as a towed sponson in the case of the initial prototype. The probe/receiver/sponson concept is of interest due to possible extension to the task of at sea refueling of USVs (Galway and Phillips 2007, Galway 2008). While these concepts show promise, they place different recovery equipment demands on the host ship.

USV STRENGTH DESIGN CONSIDERATIONS

Any USV launch and recovery system will be focused on the transition of USV weight between water and host ship structure. For USV recoveries made while the host ship is underway, there will also be a transitioning of USV propulsive power to some form of towing device, unless the plan involves some form of a drive up ramp. The rate of transition is a key factor in severity of the loading on USV and components. While a gradual transition is a nice goal, there is some indeterminacy in the recovery evolution caused by the waves and turbulence aft of the host ship with the potential to create sudden unwanted high impulse loads which makes it more of a partially random process. The hydrodynamic concerns with recovery near the stern of a ship were characterized by Sheinberg (Sheinberg et al, 2003, p11). A worst case of these loads could result in an unwanted impact between USV and host ship or cause temporary overloading of the launch and recovery equipment. Two ways to deal with this issue are a load limiting feature (such as a mechanical fuse or weak link) and/or to employ conservative initial design factors. Load limiting devices have the advantage of allowing for lighter equipment designs, but the mode of failure has to be predictable and once failure has occurred, an alternative recovery method is needed and frequently the system requires repair. Once prototypes are operational, additional load testing between USV and host ship might yield loading data which can be reprocessed in the design spiral to further optimize equipment. It is further noted that the factors of safety used by the recovery equipment need not transfer to the USV or ship design. Both USV and ship structure need to be able to safely support the equipment design load seen at the USV transition point using their associated design margins.

Perhaps the largest strength consideration facing the USV designers is providing sufficient structure to support the transitioning load from water to host ship structure. Here the method of recovery plays a substantial role. For systems that involve plucking the USV from the water, the device accomplishing the lift will need to make allowances for the rapid change in loading caused by elevation changes between USV and ship as a result of pitch cycle differences. The likelihood for potential overload during such an event is high. This concern is cause to ensure structural support of lifting points on the USV are robust. Current guidance for lifting points on boats and craft in the U.S. Navy is a factor of safety of 6 based on the ultimate strength of materials involved (NSTM 583, Section 583-7.1.1.a., p. 583-7-1). In the instance of tow or drive-aboard recovery solutions, the robustness of the USV hull will have to be evaluated for adequate support structure and skin thickness relative to the localized loads experienced when coming into contact with the ramp or bunking system provided by the host ship.

Some fleet class USVs (such as MIW & ASW) are rigid hulls designed for high performance missions. To achieve the level of high performance needed for these missions, USVs have V-hull, Tri-Hull, or similar hull forms suited more for hydrodynamics than landing support and are optimized for weight. These angles create potential point or line contact areas with flat or V-shaped bunks or ramps aboard a host ship, leading to high load areas during a recovery. The shape and strength compatibility between USV and host ship ramp/bunk system is an excellent example of design interface that needs to occur to ensure smooth load transition. Because of the variety of Off-board Organic Vehicles (OOVs) planned for LCS missions, optimizing the ramp or bunk system to a particular hull form is not possible. One method of managing this design consideration for rigid hulled USVs is to utilize a compliant and flexible support system that distributes the load over more of the USV hull and lessens the impact of shock loads.

A second major USV strength transition consideration is determining the load likely to be seen from the capture mechanism. Calculation of a theoretical tow load proves to be quite a challenge due to the number of variables involved. There are complex analytical techniques and computer simulations that can model part of the process, but the conclusion reached by Sheinberg (Sheinberg et al. 2003, p.13) was that none of the readily available computer programs at the present have the capability to calculate all the phenomena considered crucial for a stern ramp recovery operation. Since most recovery methods involve a connecting tow line, the complexity of a mathematical model would be much greater, although there have been some efforts in this direction (Roberts 2005).

Two less complex methods for getting an estimate for tow line tension involve following the procedure outlined in the US Navy Towing Manual (used for craft over 600 tons) (US Navy Towing Manual, Appendix G) or coming up with a unique relationship based on actual tow testing data. Using the US Navy Towing manual for a USV required some bold assumptions due to lack of suitable USV hydrodynamic tow data (such as assuming the USV was similarly shaped and had tow properties similar to a frigate). Even with knowledge that the process was never meant for USVs, the resulting values for tow line tension were close enough to values experienced in testing to be worthy of comparison. Shown in Table 2 is a calculation using this method. It is noted that item 17 on this table is highly influential in the calculation and suspect as it was graphically interpreted at the extreme end of a curve. The second method used in determining a relationship for tow line tension of USV involves tow testing of a particular USV and recording line tension, then using the data to establish a relationship between the primary factors (craft weight, tow speed). This method is accurate, but would be limited to a particular USV and tow assembly. Since data would be collected in an uncontrolled environment, the sea state, wind velocity, and tow heading relative to the seas may be recorded, but the discrete influence of each effect was not isolated. As a result, a simple linear expression could be fitted to the data and reasonably describe the relationship between craft size, tow speed, and tow load. This method was the method employed by NSWC CD Code 23 for developing the expression for line the tension shown in Table 3 (Whitford, 2006). It is recommended that this type of developmental testing procedure be employed by any new launch and recovery concept or USV/host ship combination to validate the results predicted from calculations. Further, if the “back-up” plan for recovering a damaged or unrecoverable USV involves towing it long distances, this data would also be useful for designing emergency towing equipment. Once actual host ships are able to tow USVs, additional data for a particular host ship/USV interface should become available and used to further refine early predictions.

TABLE 2. Calculation for Towline tension using US Navy Towing Manual

Item	Description	Symbol	Units	Source		
1	Class					
2	Tow Speed	V_{TOW}	knots		5	10
3	Tow Course	γ	Degrees		N/A	N/A
4	Tow Displ.	Δ	Long tons	Table G-2	10	10
5	Frontal Wind	A_T	Sq. Ft.	Table G-2 (estimated 6' x 5' USV frontal area)	30	30
6	Wind drag Coeff	C_w		Table G-2	.7	.7
7	Prop Area	A_p	Sq. Ft.	Table G-2	2	2
8	Hull Curve #			Table G-2	2	2
9	SS Curve #				1	1
10	True Wind spd	V_{wind}	Knots		20	20
11	Beafort SS #				3	3
12	Rel Wind spd	V_R	Knots	True wind speed and tow speed (est.)	25	30
13	Heading coeff	K		Table G-3	1	1
14	Wind resistance	R_W	Pounds	R_W=0.00506(A_T)(C_W)(V_R)^2(K)	66	95
15	Resistance factor	$R_{H/\Delta}$		Figure G-6	1.6	7.2
16	Hull Resistance	R_H	Pounds	R_H=1.25($R_{H/\Delta}$)(Δ)	20	90
17	SS Resistance	R_S	Pounds	Figure G-7 (very approximated)	500	500
18	Prop Resistance	R_P	Pounds	R_p=3.737(A_p)(V_{TOW})^2	187	747
19	Total SS Tow Resistance	R_T	Pounds	$R_T=R_W+R_H+R_S+R_P$	773	1432
20	Tow Hawser Resistance	R_{WIRE}	Pounds	Table 3-1 or 10% of R_T	37	143
21	Total Tow hawser tension	R	Pounds	$R=R_T+R_{WIRE}$	810	1575

TABLE 3. NSWC CD Code 23 USV Tow Load Equation

Tow Load= $T_{nom} = \dfrac{W}{13{,}000}((231 \cdot V_k)-534)$

W= Rated weight (maximum displacement in pounds)
V_k=Rated Speed for recovery in knots

Limitations:
Tow Speed: 5 knots <speed<13 knots (note this is linear approximation of a non-linear event)
Boat Length: up to 42 feet
Boat weight: up to 22,000 lbs
Steady Towing, not during capture
Equation meant for calm waters.
Dynamic factors should apply to cover seas > than sea state 3.

TABLE 4. Comparison between Tow manual and NSWC CD Code 23 USV Equation

Method	Tow Manual Method	NSWC USSV Test Equation
5 Knot Steady State Tow Force	810 lbs	1050 lbs
10 Knot Steady State Tow Force	1575 lbs	3005 lbs

TABLE 5. Latch Mechanism Rated, Design and Tow Loads

Tow Speed (Kts)	SS Tow Force (lbs)	Rated load (lbs)	Design Load (lbs)	Test Load (lbs)
5	1050	3150	15,750	4,725
10	3005	9015	45,075	13,523

Given a value for the steady state tow load, load factors can be applied using existing engineering judgments. The NSWC CD Code 23 latches used the tow loads shown in Table 4, then multiplied by a factor of 3 to get the rated load (factor for dynamic effects) and then by a factor of safety of 5 to get a design load (applied to ultimate strength of materials). Loads used are listed in Table 5.

Although these numbers may seem high to designers, they are of similar magnitude to the factors of safety used by the US Navy Towing manual.

There is one additional operation load worthy of discussion that is likely to be experienced during any dynamic recovery effort. During recovery cycles involving line capture, the line is presented in some manner by the simulated host ship at controlled speed and heading. The USV accelerates from some position, either autonomously or under human control and overtakes the presented line causing a latch to occur. The USV then rapidly decelerates before overrunning the presented line or host ship. While deceleration occurs, the tow line goes slack and until the tow ship makes it taut and then accelerates the USV to tow speed, producing a jerk. The severity of this jerk is a function of elastic properties and length of the tow line, the relative difference between the speeds of the USV and the simulated host ship, relative weight differences between the two craft involved, geometry of the USV hull and the orientation of the USV at the time the rope is made taut. Typically during testing, the USV would turn slightly as the simulated host ship took up the tension in the towline. The orientation and speed of the USV was then quickly directed to match that of the tow craft by the force on the towline. Depending on how much the USV had turned to one side or the other, a rapid yaw acceleration coupled with the rapid linear acceleration towards the simulated host ship towing the presented line was observed. The USV was never observed turning any further than perpendicular to the course heading during testing. This was due largely to the relatively short length of the towlines. However, if tow lines were substantially increased in length, and the initial yaw angle was greater than 90 degrees with the wrong combinations of USV pitch and wave locations occurring, then the jerk load might induce a moment that tended to capsize the craft. In a yaw angle of 180 degrees or more, there would also be a risk of fouling the propeller. The latch mechanism used in prototype testing had a rope sensor, which is set up to enable the USV controller to slow gradually and soften the transition, which should be a consideration for future recovery systems as well. This load is a design consideration in line recovery methods for all interface equipment on the USV, the host ship, and recovery system.

USV HYDRODYNAMIC DESIGN CONSIDERATIONS

Protrusions associated with the launch and recovery system that are at or below the waterline add drag to the hull, which translates to loss of mission capability. In addition to the drag caused by the protrusions, large bow mounted vertical flat surfaces, such are present on the external design, create a potential control issue as any wave induced side force has a large moment arm for producing an unwanted USV yaw. Another undesirable hydrodynamic characteristic of protrusions is the generation of spray as they are pushed through the water. While just an annoyance for humans, on the USV this will translate to additional sea spray for externally mounted antennas, sensors, or mission related equipment causing increased corrosion, water intrusion issues, and possibly icing issues. Obviously, recovery systems that do not have a component in the water are immune to this consideration. On that note, the particular attractiveness from a hydrodynamic viewpoint of retractable components becomes apparent. This was a recommendation made as part of the FY07 ONR testing and discussion with NSWC CD Code 23. The methods for accomplishing this recommendation include making components more retractable, more hull conformal, or generally smaller. Each of these methods creates a design judgment involving trade-offs with cost and reliability, as complexity increases from retract ability or conformal design, and capture percentage as general aperture size is decreased.

USV OPERATIONAL RISK DESIGN CONSIDERATIONS

Launch and recovery evolutions of any kind demand a rapidly increasing combination of sensory, decision making, and craft response as the distance between USV and host ship closes to zero. Until such a time as the autonomous capabilities of the USV meet or exceed the skills and predictive response capabilities of a skilled boat driver, there will be some inherent increase in risk associated with a fully autonomous recovery. On the plus side, there is no human aboard the USV so the acceptable risk level away from humans can be marginally higher. The long term goal of the NSWC CD Code 23 and ONR effort is to make the launch and recovery evolution predictable and reliable enough to be an acceptable risk. Achieving this goal will involve determining in advance as many of the possible emergency scenarios as possible and programming an acceptable response into the electronic control software in the USV. A chief concern with USVs involved in recovery operations is a collision with either ship or recovery gear. The expected location of any floating or towed recovery equipment will need to be identified for the USV and this information updated during recovery evolutions. Similarly, the location of the furthest most part of the host ship will need to be identified. USV closing rates on any floating recovery device or ship will need to be initially groomed so that ample time exists for the success of a recovery attempt to be determined and evasive action taken to avoid overrunning any recovery equipment or impacting the host ship if the attempt is unsuccessful. Provisions should be made for grooming the control system and determining the slow speed response characteristics of any USV considered for use with any host ship. Based on observations made during the testing during FY07, these software grooming considerations are achievable (NSWC CD-23-TM-2007/31 & NSWC CD-23-TM-2007/32, November 2007) . However, the grooming will need to be a continually checked and updated process.

AUTONOMOUS LAUNCH AND RECOVERY EQUIPMENT DESIGN CONSIDERATIONS

The next link in the recovery system chain following the USV interface is the autonomous launch and recovery equipment. Equipment used for launch and recovery serves as the means by which USV stability, control, and weight is transitioned from the water to the host ship. This equipment has to be sensitive enough to allow sensing and connection to the USV, and once connection is made, be rugged enough to handle the load transition to the host ship. In the instance of current line capture autonomous recovery methods, equipment consists of: a bow mounted latch mechanism on the USV, a recovery line; a means to present the recovery line to the USV; a means to transition the force required to propel the USV; and finally a means to transition the weight of the USV from the water to the host ship. In addition to this hardware, the USV either needs to be provided with a sensor and control system that can accomplish the unique demands of an autonomous recovery or be fitted with a specialized sensor and control system that is capable of this function. Correspondingly, the host ship or towed body will need to be fitted with portions of this system and have it integrated into the ship's electronic network. While many of these components have been in existence for many years, having them all work together to provide a functional recovery system is a new technology.

During operations, a recovery line is presented by the host ship on or above the water with enough resistance or tension to allow latching to occur. The current latch mechanisms require about 5 lbs of resistive force provided by the rope drag or tension. Towing of just a line in the water of sufficient size and length to be used for USV recovery generally provided enough resisting force for latching to occur. The latch height in each latching device was selected based on the static waterline of the USV. During testing evolutions, in calm water latching evolutions, the line would make it to the latch with very little guiding required by the lower guide. Key design issues include proper angular orientation of lower guide with the bow and the smoothness of both surfaces to allow sliding of the recovery line to the latch. As the sea state increased, the effectiveness of the lower guide was determined by the location of the USV bow in a pitch cycle as it reached the recovery line. When the bow was up, the towline would be lifted from the water by the ramp of the lower guide arm and directed to the latch. Occasionally, when the line was lifted from the water, the drag force on the portion out of the water went almost to nothing, making the line limp. Latching was then dependent on where the USV was in the pitch cycle. If the bow was heading down the guides directed the line to the latch and the buoyancy of the line being forced into the water assisted with the latching force. If the bow was heading up in the pitch cycle, the line occasionally was pulled off the guide by the drag force of the part remaining in the water and the USV overran the line, causing an unsuccessful latch attempt. Once latching occurred, transition of propulsive force for the USV goes to the host ship and eventually, transition of the USV weight to the host ship is accomplished via the host ship's recovery method.

EQUIPMENT STRENGTH DESIGN CONSIDERATIONS

The launch and recovery equipment used in an autonomous USV recovery will be subjected to the same loads as towing gear and rigging gear used for lifting boats and craft at sea. The uncertainty in operational sea conditions associated with predicting relative motion possibilities between USV and host ship, and the lack of human judgment in the recovery decision matrix causes hardware designers to focus on a worst-case scenario.

In addition to the US Navy Towing manual safety factors reported in the previous section for towing gear, the lines have their own set of safety factors. Factors of safety of 10-12 for synthetic lines and 4-8 for polyester lines are provided, with the caveat that an additional factor of safety of 2 should be used for lines less than 8” in diameter (US Navy Towing Manual, Table 3-2, p. 3-8). The lines used for recovery operations typically are high modulus polyethylene (HMP) lines. These lines have a very high strength and low elongation characteristics. The high modulus version floats. They are abrasion resistant and are not prone to rot. Elongation is 3% at 40% of breaking strength (very stiff). Characteristics of a typical rope are provided in Table 6.

Once latching has occurred, the rope doubles over the latch, so the net breaking strength of the line is twice the breaking strength of the breaking strengths in Table 6, ignoring losses from bends, worn rope and chaffing. At the USV to recovery equipment interface, ideally a rope pull in excess of breaking strength would cause the rope to part before any damage was done to the USV latching device. Doubling the breaking strengths from Table 6 and comparing them to the 45,075 lb design load from Table 5, the reader can see that ropes at or in excess of 5/8” diameter are greater than the design load on the recovery latch. Use of these ropes could impart damage on the latch mechanism (or ship connection) prior to parting the rope. In the event such an overload is seen, the connection between the latch mechanism and the USV should be designed to fail prior to causing catastrophic damage to the USV hull. Two potential design risk mitigating factors for this occurrence would be the use of either a mechanical fuse (Whitford, March 2006) of some kind or designing an overload tension release mechanism for the USV latch or other connection point. It is easy to see that the recovery line size can have a large influence on the failure point. Trying to accommodate ropes of various sizes with one latch mechanism is problematic if the rope is intended to be the weak point in the system. A programmatic way to prevent this occurrence would be to specify the interface line diameter and breaking strength for the recovery system.

TABLE 6. Breaking strength of a typical HMP rope (Spectra© 12 Strand Rope (Vendor’s data from Puget Sound Rope Company))

Line Size	Line Weight	Average Breaking Strength
3/8”	3.7 lbs / 100ft	13,900 lbs
7/16”	4.2 lbs/100 ft	14,800 lbs
1/2”	6.4 lbs/100 ft	22,500 lbs
5/8”	10.6 lbs/100 ft	36,600 lbs
3/4”	13.3 lbs/100 ft	43,200 lbs

Just as with the USV interface, there should be a planned failure mode for transitioning loads from the USV to the host ship in the event of an unexpected overload of the launch and recovery equipment. Since a planned failure mode is a common requirement for all three components of the autonomous launch and recovery system, the order of failure is a further consideration. In the hierarchy of component strength related failures, it is more desirable to have replaceable launch and recovery equipment than to have something aboard either the USV or host ship fail and require pier side repair or jeopardize the craft. That being said, the need for a back-up plan for recovering the USVs at sea becomes evident. If the recovery equipment is the planned failure mode, a secondary design condition for both USV interface and host ship interface becomes the ability to survive the breaking load of the recovery equipment. Any mode of planned failure should minimize the amount of energy stored in a device that might be released in the form of flinging metal objects, such as parts of a mechanical assembly or rigging gear, particularly in areas where personnel might be located. A secondary consideration would be to minimize the chances that broken lines become entangled in the propellers of either craft. This sort of predictive operational planning at the design level demands a high level of communication and shared information between the designers of all three major parts of the autonomous launch and recovery system.

EQUIPMENT OPERATIONAL DESIGN CONSIDERATIONS

Once the USV is in position, by far the greatest consideration in grappling system design experience by the NSWC CD Code 23 team was the difference in vertical position of connection points on both USV and host ship. The NAVY UNMANNED SURFACE VEHICLE MASTER PLAN states that developmental goals for USV launch and recovery systems should include operations at higher speeds and higher sea states (PEO MLW & OPNAV N86, July 2007). The sensitivity of the boats and craft and any floating recovery equipment to waves can create a substantial range for possible vertical position of connecting components at recovery. Even the smaller waves experienced in sea state 2 or 3 conditions have a substantial effect on autonomous launch and recovery efforts. At test recovery operations speeds (5-10 knots), the USV is just riding over the waves and swells. The relative length of craft to length of wave becomes an issue for small USVs. Some useful extracts from a Sea State Table are provided in Table 7. Note that there are several definitions of sea state and that significant wave height does not mean the largest wave encountered.

TABLE 7. Sea States from NATO Standard Agreement (SNAME,1989)

Sea State	Wind Speed (kts)	Significant Wave (ft)	Significant Range of Periods (sec)	Average Period (sec)
1	0-6	0-.3	1-4	-
2	7-10	.3-1.6	1.5-6	3.3-12.8
3	11-16	1.6-4.1	2-7.5	5.0-14.8
4	17-21	4.1-8.2	2.5-9.5	6.1-15.2

The length of the waves in Sea State (from peak to peak) is significant when compared to the length of the USV (about 40’) and less significant to the length of a typical host ship (such as LCS concepts (379’-419’)). During the impact between a wave and the USV, the USV’s bow initially cuts through the wave, but as the wave passes by, its force lifts the bow of the USV until the USV’s center of gravity is on the other side of the wave, then gravity causes the USV’s bow to drop down, often into the path of the next wave. This effect is amplified by any USV forward momentum and tow force. This motion is a form of pitch, but would be unique to boats and craft in which the relative wave lengths were significantly small enough to be close to the length of the craft. Heading also plays a part in the severity of the pitching condition of the USV. A heading into the waves will increase the relative speed a wave affects the USV, and conversely a heading that follows the seas will add to the period between waves actually experienced by the USV without changing amplitude. This effect was confirmed by NSWC CD Code 23 USV latch testing, as recovery percentages were almost always higher in following seas. The effect can also create an additional towing load as a USV pitched down into an on-coming wave while under tow could have the wave hit a portion of the top surface of the USV and be drug through the wave by the tow line. While the USV is exhibiting one type of pitch pattern, any floating or towed object behind the host ship that might be presenting a line to the USV for recovery could be exhibiting a different pitch pattern, either rolling with the waves or cutting through the waves, depending on buoyancy and hydrodynamic factors. A final environmental design consideration is the operation of the equipment in high wind or Arctic conditions. The host ship may travel to Arctic environments where high wind, freezing temperatures and ice creates an operational envelope that precludes conducting a safe autonomous recovery with planned methods. Recoveries in such conditions have yet to be tested.

For current LCS recovery concepts, the relative pitching motion between the USV and the recovery line interface is the key factor in the success of recovery operations. For the concept to work properly, line orientation at the recovery intercept should be parallel to the water surface plane and perpendicular to the direction of travel, approximating a line perpendicular to the longitudinal axis of the USV ideally. The vertical position of the line, although at different heights off the water for the different concepts, should not change its vertical position substantially during recovery operations. Both developmental designs employ a "V" shaped aperture, with the large opening oriented forward. The upper part of the aperture is formed by the rake of the bow of the USV or housing of the latching device, and the lower part is formed by a rotatable retracting bar. The distance between the tips of the "V" shape dictates the possible entry area for a recovery line. Where the tips of the entry are relative to the recovery line at the time of intercept is highly dependent on USV pitch. For instances where little or no pitching occur, or where any pitch is down, the probability of capturing the recovery line is high. However, in instances where the waves are large enough to cause a substantial upward pitch, the bow of the USV and the lower guide can come out of the water and go over the recovery line. Test results show this effect is mitigated somewhat by the initial position of the line off the water, with a higher presentation height being favored. During recovery testing, there were several instances in which the lower guide went over the line, but none where the line went above the upper guide. This may change depending on the fullness of the bow.

A second factor in determining how the recovery line gets presented to the latch mechanism is wake created by the host ship. Here, the size of the host ship, method of propulsion, and location of propulsors all contribute to the swells that a craft in recovery position experience. The effect that this has on recovery of the USV is dependent on many other conditions such as distance behind the host craft, host ship speed, and line presentation method. Many of these things are simple to correct, but all represent conditions that should be considered in the work-up grooming evolutions between host ship and USV prior to deploying the system.

The size of the aperture and its vertical location relative to the waterline of the boat are two design elements that can be controlled to influence the probability of success for line recovery. The vertex of the aperture and the latching mechanism are best located where the least amount of effort is required for directing a line to the latch mechanism. A location for the vertex at the USV waterline seems a logical starting place and yielded favorable results. However, determining the exact waterline position for a USV that will have different loading for different missions and a different trim for different speeds is far from an exact prediction. For designs that employ an external style latch mechanism, there is the potential to improve performance by repositioning the latch mechanism vertically to increase latch probability as loads and trims vary. The location of the internal style latch mechanism is fixed once installed on the USV.

Although the exact relationship between size of aperture and the probability of capture for various sea states and headings is yet to be determined, it is easy to concede that a larger aperture will likely increase the probability of at least collecting a recovery line. The question then becomes one of the trade-offs associated with a large aperture, and the answer involves hydrodynamic and other complex engineering trade-offs in USV design which can further impact mission performance and cost of the USV. Determining the best answer for a particular USV and mission demands knowledge of the trade-offs by an individual or organization that has over-arching responsibility for both sides of the USV and autonomous recovery equipment design equation. Finding the proper balance between USV launch and recovery equipment design goals and USV missions might justify a separate group devoted solely to integrating needs early enough in the design process of both elements to insure a win-win situation at recovery time.

Although making the initial connection between USV and host ship is the most important operational design consideration, it is far from being the only one. Another consideration is the need to break connection at any time during recovery for any reason. If recovery operation observers see something wrong with the USV (maybe a mine is attached), have a problem on the shipside of the recovery, or something causes a safety concern, the capability of releasing the USV must exist. The release could occur at either end of the operation, but to avoid the cost of another recovery rig, the release should properly occur at the USV and recovery equipment interface. On the current line grappling latch designs the recovery line can be released remotely. The ability to remotely release the recovery line while under tension is an innovative latch mechanism feature. This feature uses a linkage actuated by an electric linear actuator to release upon command using the force provided by the line tension to assist in the release. While this feature adds complexity to the design, being able to release once connected provides a measure of safety for both USV and host ship in the event of an emergency. Coupled with this feature is the need to be able to remotely reset the mechanism for the next capture.

EQUIPMENT LIFE CYCLE DESIGN CONSIDERATIONS

Autonomous launch and recovery of USVs adds a measure of complexity to the boats and craft recovery process and adds a system of equipment on both the USV and host ship that will need to be maintained, serviced, modified and supported. The marriage of close fitting mechanical components and electrical sensors and actuators with salt, sand, and the impacts expected during repeated recoveries will demand inspections, maintenance, and some on-board spares provisioning for the host ship. While these all represent long term costs to the customer, there are several things that can be done from a design standpoint which can minimize these impacts. The first set of design considerations to minimize future reliability problems involve following good marine design practices. This includes but is not limited to: use of corrosion resisting materials; minimizing parts and joints; and providing watertight electrical components, including galvanic protection, lubrication points and sealing mechanical joints where possible. The next set of design considerations involves access to equipment that is likely to need maintenance or service.

By virtue of size, this should be less of a problem for equipment on the host ship side of the equation. The problematic area is likely to be on the USV. There are some attractive features associated with integrating the USV side of the connection into the USV, chiefly reduced hydrodynamic impact and reduced long-term exposure to the direct marine environment. However, care should be exercised when accomplishing this endeavor to provide for equipment removal and service. NSWC CD Code 23 latch mechanisms each provided for removal of the entire device from the bow of the USV for service, maintenance, or replacement. One service strategy discussed involved having a rotatable pool of devices that could be overhauled and serviced while others were in use. In the case of the internal mounted style of device, the host USV can have the device removed entirely and the opening replaced with a bow plug. A final design consideration would be to try and standardize the recovery system as much as possible and make components modular. Modularity will allow potential swapping of units between USVs, potentially reducing the number of on-board spares required to keep latches in service. Allowing different designs by different vendors will create a parts supportability problem.

HOST SHIP AUTONOMOUS LAUNCH & RECOVERY SYSTEM DESIGN CONSIDERATIONS

The final link in the recovery system chain is design considerations for the host ship. Autonomous recovery of a USV will require special equipment and facilities aboard a host ship, and depending on the size of the USV, may require a specialized area for recovery. In such instances, unless autonomous recovery of USVs is the primary purpose of the ship, the equipment required for autonomous recovery will have to co-exist with equipment required for the primary mission of the ship. The system by which the USV weight is transferred to the host ship will need to be designed such that the transition is gradual, yet be robust enough to accommodate the two body dynamic relative motion issues brought about by environmental conditions.

HOST SHIP INTEGRATION DESIGN CONSIDERATIONS

An LCS ship is designed to act as host ship for many different types of Off-board Organic Vehicles (OOVs), creating many potential combinations of hull shape, craft weight, and recovery methods. LCS baseline requirements identify a set of OOVs to be accommodated during the initial prototype design (list of craft provided by Johnson et al, 2005, P6). This requirement gives the recovery system baseline designer a reasonably well defined set of accommodation requirements. USV recovery and any new OOVs added to the LCS or other fleet of support ships will need to either use existing recovery facilities and equipment or bring aboard what is needed and require reconfiguration. New equipment cannot preclude the recovery of existing OOVs (unless so directed) and the amount of reconfiguration required has to be consistent with the ship’s mix of OOVs for a particular mission. These ship integration considerations create a demand for the recovery system designer to be aware of both existing and future ship recovery equipment and USV designs. Compatibility of new recovery equipment with existing shipboard recovery equipment will greatly influence the cost of integrating a new recovery system into the fleet. Concepts for launch and recovery which are radical and require a large amount of re-engineering into existing USVs and host ships need to have the cost of the total reconfiguration requirements (old OOVs, old host ships, etc.) included in the life cycle cost of the system when comparing a new system to the existing system. Another aspect of the host ship compatibility is the stowage required for components in a new recovery system.

Space required and weight added to the ship are primary considerations. Additional issues include special needs for lifting heavy components with the ship's overhead crane, storage of hazardous materials, and maintenance of any specialized equipment used exclusively for recovery of USVs. A final ship integration design consideration is the amount of time and specialized expertise required by the crew to conduct an autonomous recovery of a USV relative to the amount required by other OOV recovery evolutions. Launch and recovery of a USV can require more crew than a regular small craft as has been shown with Spartan and Seafox (Gayle 2006). Crew impact concerns involve the total number of crew required to accomplish a recovery evolution, the amount of total man-hours spent, and the specialized training required for equipment operators. The unmanned recovery aspect would help reduce the host ship personnel requirements to recover small boats and reduce the danger to sailors involved in these situations (Boland 2007). Training for operations, maintenance and overhaul will need to be worked into the existing training requirements for the appropriate rates. This subject was discussed at length by Gayle (2006). In the case of the latch mechanisms developed by NSWC CD Code 23, the recovery system for the host ship (the LCS in this case) had already been determined by the competing LCS ship contractors and the recovery system equipment designed had to be compatible with these concepts. It is important to point out that USVs, LCS ships and associated autonomous launch and recovery equipment are very much emerging technologies and adapting to change will be a part of future design efforts.

HOST SHIP METHOD OF USV WEIGHT TRANSITION DESIGN CONSIDERATIONS

In any recovery operation, autonomous or otherwise, ultimately the weight of the USV will be removed from the water and brought aboard the host ship. This should not be trivialized because transferring 10,250 kg (22,600 lbs) of weight from the water to a ship at sea is no simple feat. Add to this the fact that both will be underway during the transition, and the difficulty is clear. Again, the pitching motion is the primary concern, but now the host ship is contributing to the relative motion. Using Mil-Std-1399 as a reference for expected pitch at different sea states, it is observed that for a ships in the 350-500' range, 1 degree of pitch is expected for SS4 conditions and 2 degrees of pitch expected for SS5. Assuming the ship center of gravity is in the center, the range of vertical motion at the stern is 3'-4.4' for SS4 and 6.1'-8.7' for SS5. Although values are not given for SS2 or SS3, it is reasonable to assume that some fraction of the SS4 values will be present. This is a substantial design consideration because the design range for possible differences in heights between the USV and the host ship is additive. Also a factor is the relative pitch periods of these ships, which according to Mil-Std-1399 will be about 6 seconds. The relevance of the 6 second ship period is only as a comparative reference for the USV pitch period, which will be substantially faster, meaning the USV and ship will be pitching at different frequencies. Recovery system designers need to plan for a successful recovery in the extreme ranges of any sea state for which recovery is qualified. Sudden relative changes in height between USV and host ship can create load pulsations and uneven loading in the lifting lines. Sudden relative changes in height also change load conditions in a ramp or bunk support method by rapidly changing the position of the waterline during a recovery. Both the range in possible vertical location during load transition and the relative pitch cycle differences between USV and host ship create the need for a flexible weight transition method that is robust enough to handle all variations without damaging the USV or host ship during normal operations.

Although a skilled boat operator might be able to gain some advantage by timing a particular event to occur at some point during the relative difference of the pitch cycles, an autonomous recovery operation will take longer than many pitch cycles and where in the recovery process the USV is during a particular pitch cycle of each craft is for the most part random. As of this moment, the sensor and control systems aboard the USV have no provision for using pitch cycle information to make any corrections. Thus, the design consideration that must be made is to make sure that the recovery system can accept any combination of relative pitch cycle difference during a recovery. The flexibility to be able to handle this range at every sea state during the transition of the USV weight to host ship without damaging USV, host ship, or recovery equipment and maintaining a safe working environment for personnel is a significant design consideration. In designs that transition the USV weight by lifting, this will involve some compensation in the lifting device to avoid over-tensioning or slack rope conditions. For designs where transitioning occurs from below, this involves some form of compliant transition material or system that can compensate for the changing vertical distance.

HOST SHIP OPERATIONAL DESIGN CONSIDERATIONS

There are a number of operational design considerations associated with the host ship that can influence recovery operations and the design of recovery equipment. Since operations will be conducted while underway, hydrodynamic properties of the host ship such as wake and propulsion system turbulence can influence the water where the recovery is to take place. The mitigation for this design consideration involves testing the hull and USV combination to see what the effects these characteristics have on recovery procedures. A second operations consideration is an operational plan for USV recovery if things go wrong or if the host ship is stopped in the water. Some thought should also be given to a plan for the different type of emergency situations that could occur during recovery. Some examples include:

- USV damaged from mission or on fire, or is leaking fuel
- USV has mine attached or otherwise has something unwanted aboard
- USV impacts a submerged object or flips during recovery attempt
- Recovery gear fails or becomes entangled
- Multiple USVs return from mission requiring different recovery gear
- USV is returning with hang-fired ordnance.

Relative to launch and recovery of USVs, the UNMANNED SYSTEMS SAFETY GUIDE For DOD ACQUISITION Design Safety Precept 17 cites the Unmanned System (UMS) shall be designed to assure safe recovery. The precept identifies three main points: 1) the design supports a recovery process that is adequately safe in non-normal operations; 2) the design supports a recovery process in degraded or damaged conditions; and 3) the system is designed to be safed. Safed is defined as the sequence of events necessary to place systems or portions thereof in predetermined safe conditions. Design Safety Precept 17 makes reference to Operational Precept 2, which states that an Unmanned System (UMS) shall be considered unsafe until a safe state can be verified (Office of the Under Secretary of Defense (AT&L), June 2007 p. 92, p. 64). Since the ‘What if…’ scenario list is large, the answers to every question need not be answered completely at this point in development, but if the answer could involve a modification to or a need for a change to the design of the recovery equipment it should be included in developmental work. A third and final consideration involves a plan to get specialized payloads (ordnance, injured personnel, sensitive & bulky equipment, etc.) from the USV quickly. These operational scenarios are expected to continue to evolve as the war fighters put equipment to the test. One method of capturing some of the operational design considerations would be to include a representative from the fleet in key design discussions to offer a potential operator's perspective.

CONCUSIONS

USV Launch and Recovery Equipment Interface Design Considerations

•USV Weight sensitivity-Amount and location of added weight to USV can reduce capability and impact stability. Latch mechanism weights of 100 lbs or less are possible.
•USV Geometry-Changing the length of the USV or adding protrusions can create transport problems and increase risk of snagging during operations. A bow mounted device will be prone to impact issues.
•USV Strength-The transition of loads from the water and USV propulsion system to the host ship will create unique loads on USV structure. These loads include weight of the craft, and tow loads and jerk loads for USVs using a line recovery method.
•USV Hydrodynamics-Recovery equipment has the potential to add drag and control concerns.
•USV Risk-Control systems responsiveness and software programming need to be groomed for each USV and host ship combination. USV controller should have planning for emergency scenarios programmed.

USV Launch and Recovery Equipment Design Considerations

•Strength-Equipment must be able to handle USV launch and recovery loads with a level of risk that is identified as acceptable by the Navy. These loads include towing and jerk loads with factors accounting for any combination of dynamic sea conditions expected in the operational envelope. There should be a planned mode of failure when loads are exceeded.
•Operational-Recovery devices should have the ability to release in an emergency and reset for the next recovery attempt. For line catching concepts, the expected percentage of capture during all conditions of the operational envelope should be a design consideration
•Life Cycle-Launch and recovery equipment designs should be designed for corrosion resistance, minimal maintenance with access considerations for any planned maintenance, and favor modular design approaches for quick shipboard replacement.

USV Host Ship Launch and Recovery Design Considerations

• Equipment-Equipment and methods used for USV launch and recovery need to be compatible with equipment and stowages used by other OOVs aboard the same host ship.
• Weight Transition-The means by which USV weight is transitioned from the water to the host ship needs to minimize the severity of loads on USV and recovery equipment during all sea conditions in the operational envelope.
• Operational –Host ship and crew should have a back-up plan for recovering USVs and damaged or partially functional USVs. If USVs are involved in a mission that involves weapons, then ordnance handling equipment and handling methods should be included in the shipboard design. Special considerations for a USV that is contaminated in some way or leaking fuel should be provided.

RECOMMENDATIONS

The design considerations for developing launch and recovery equipment provided by this effort should be used as a baseline for current and future development efforts. The list is in no way comprehensive, but should identify some of the important engineering value judgments associated with launch and recovery equipment design. The logical extension of this preliminary effort is to ask "What should be done next?" In that light, the following areas show potential for benefit from increased exploration.

- An investigation into the benefit of establishing an expression for USVs similar to that in the US Navy Towing manual for theoretically predicting steady state towing loads of USVs and small boats and craft involved in launch and recovery

- An investigation into jerk loads encountered during recovery processes involving line capture to help quantify the design target. Modeling and validation through testing should accompany this investigation.
- An investigation into the relationship between line capture device aperture and location relative to craft waterline could be established for various sea states
- An investigation into a grooming procedure for a USV control system used in launch and recovery
- An investigation into the best way to administratively coordinate the integration, evolution, and sustainability of launch and recovery equipment with the growth of USV usage in the fleet and with other services (USCG, U.S.ARMY, NATO, etc.)
- An investigation into developing sensors that could sense pitching cycles of both host ship and USV and time a recovery as a skilled driver might do could improve results
- Continued development in recovery devices that are more retractable, conformal to the hull, or otherwise minimize hydrodynamic impact on the USV.

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