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## **Autonomous Refueling of Unmanned Vehicles at Sea**

### **ABSTRACT**

Refueling of Unmanned Surface Vehicles (USVs) at sea poses unique challenges for equipment design on both the USV and the host ship. USV refueling demands that a grappled connection be made between USV and host ship, followed by the challenge of making a fluid transfer connection remotely from the host ship. Providing the host ship the capability to refuel a fleet of USVs without the need to bring the USVs aboard the ship enhances mission efficiency. The benefits include increased USV mission time, reduced host ship exposure time, less risk to personnel involved in a recovery operation, and the possibility of refueling multiple USVs. The development of a common refueling device for use on USVs also offers the potential for receiving fuel from other sources. This increases the number of potential fuel donors to any ship, submarine, buoy, floating platform or purpose-built refueling USV. This paper identifies some of the existing concepts, design challenges, and on-going development for providing an autonomous refueling capability for USVs. This paper is based on development work at Naval Surface Warfare Center, Carderock Division, Code 23, funded by ONR (Code 33) Unmanned Sea Surface Vehicle program and a recent report prepared for NAVSEA 05D1 as part of a Cross Platform Systems Development task.

### **INTRODUCTION**

Logistics support of Unmanned Surface Vehicles (USVs) at sea is an ancillary but realistic operational and design concern for those involved in the development of both USVs and potential host platforms. One of the most basic logistics support needs for these craft is the need for a quick and efficient means of getting fuel. While refueling of manned vessels underway is

part of normal operations, the concept of providing fuel autonomously is not part of the current Navy Refueling-at-Sea (RAS) program. Autonomous refueling of USVs adds in the constriction of not having anyone aboard the receiving ship for human support or observation during refueling operations. This makes refueling operations for a USV radically different from current refueling at sea operations. The path towards minimizing USV and host ship exposure during autonomous refueling operations demands a rapid refueling method. The development of autonomous refueling methods and technology should keep a parallel pace with host ship and USV development to ensure optimal and timely logistical support for USVs entering the fleet.

The current plan for refueling USVs at sea is to bring them aboard the host ship to refuel. This adds a fairly time consuming and risky operation to the need for additional fuel. Requiring a recovery for refueling also limits the number of USVs or Off-board Organic Vehicles (OOVs) that can be serviced at one time. In the instance of multiple boats returning at one time, requiring recovery for refueling further adds the constriction of refueling sequence (who gets there first, needs fuel the most, etc.) to logistical planning.

Multiple efforts are underway exploring concepts to deliver fuel to USVs in a more efficient manner including work inside and outside the government. Naval Surface Warfare Center, Carderock Division (NSWC CD) Code 23 has been involved in a few of these efforts and is presently working on the development and testing of a device that enables fuel transfer to existing USVs. Outside the government a Small Business Innovation Research (SBIR) task has been developed to create a conceptual at sea fueling system for USVs (Navy SBIR 2007.3-Topic N07-204, Unmanned Surface

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<b>14. ABSTRACT</b> Refueling of Unmanned Surface Vehicles (USVs) at sea poses unique challenges for equipment design on both the USV and the host ship. USV refueling demands that a grappled connection be made between USV and host ship, followed by the challenge of making a fluid transfer connection remotely from the host ship. Providing the host ship the capability to refuel a fleet of USVs without the need to bring the USVs aboard the ship enhances mission efficiency. The benefits include increased USV mission time, reduced host ship exposure time, less risk to personnel involved in a recovery operation, and the possibility of refueling multiple USVs. The development of a common refueling device for use on USVs also offers the potential for receiving fuel from other sources. This increases the number of potential fuel donors to any ship, submarine, buoy, floating platform or purpose-built refueling USV. This paper identifies some of the existing concepts, design challenges, and on-going development for providing an autonomous refueling capability for USVs. This paper is based on development work at Naval Surface Warfare Center, Carderock Division, Code 23, funded by ONR(Code 33) Unmanned Sea Surface Vehicle program and a recent report prepared for NAVSEA O5D1 as part of a Cross Platform Systems Development task.				
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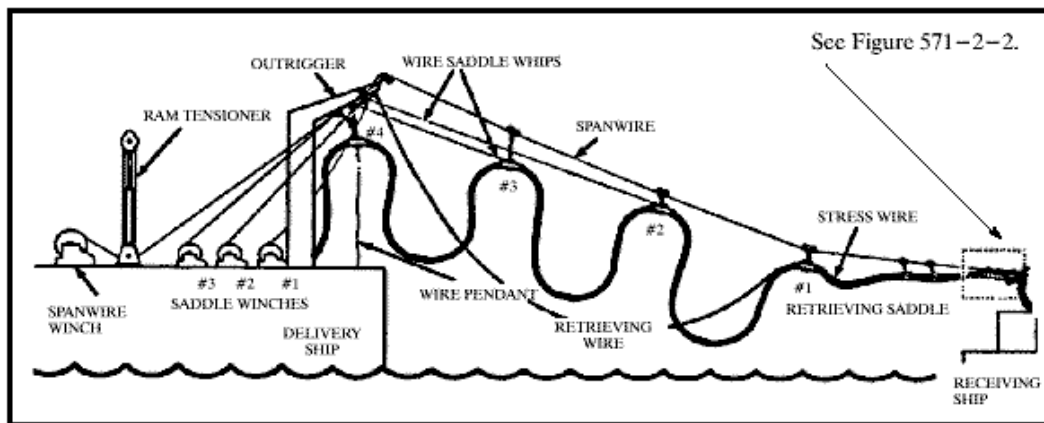
Vehicles (USV) At-Sea Fueling, Opened 8/20/2007, closed 9/19/2007). The purpose of this paper is to identify some of the existing concepts, design challenges, and on-going development for providing an autonomous refueling capability for USVs.

## BACKGROUND

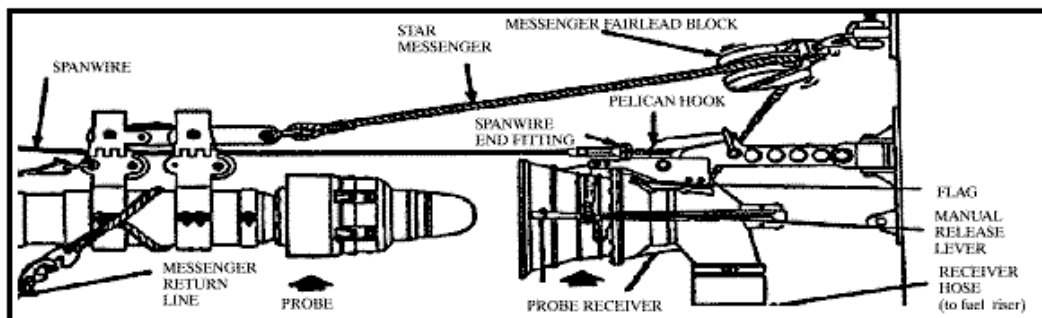
Transfer of liquid cargo at sea is a long standing naval process with systems, equipment, and procedures that have evolved over a long period of time. As shown in Figure 1, the most widely used method is the Standard Tensioned Replenishment Alongside Method (STREAM) (NSTM 571, Section 571-2.1.2, p. 571-5). This method involves passing a wire rope between ships underway on a parallel course. The wire rope (called a

spanwire) is maintained at a constant tension by a ram tensioner and rope is paid out or in-hauled to compensate for distance variations between ships during a transfer. Suspended from this wire on trolleys is the fuel hose assembly. The fuel hose assembly consists of the hose, a sealing probe on the end, and wire saddle whips. The wire saddle whips connect to the support trolleys and allow the hose to be festooned without crimping. The hose is passed to the receiving ship using a messenger line that is thrown or shot over from the supply ship, then up-sized and eventually used to pull the hose. When refueling is completed, the hose is pulled back by winches aboard the supply ship. There are also non-STREAM Spanwire and Spanline Rig variations of this arrangement, which require the winch operator to manually regulate spanwire catenary

**FIGURE 1. Navy UNREP (Ibid, p 571-6)**



**Figure 571-2-1. Fuel STREAM Rig - Single Hose with Probe**



**Figure 571-2-2. Single Hose Fuel STREAM Rig with Probe**

in response to ship roll and separation (NSTM 571, Section 571-2.1.2, p. 571-7). Existing side-by-side methods require a large amount of human interaction on the refueling ship side. The tension required to keep the hose catenary out of the water would likely make it difficult for the USV to hold station while re-fueling and not be drawn towards the host ship. Perhaps a more likely refueling scenario for USVs would be astern refueling. In the astern refueling method, the delivery ship streams a single-hose rig and the receiving ship maintains station astern and outboard of the delivery ship while receiving fuel (NWP 4-01.4, Naval Warfare Publication – Underway Replenishment). In the case of astern fueling with a 2-1/2 hose, the refueling craft is 200-300' behind the stern of the source ship (Ibid, p. 5-28). Fueling of manned boats from U.S. Navy ships is currently done by bringing the boat alongside the delivery ship, tying up at designated stations, securing appropriately, and then providing fuel with 1-1/4" hose with quick-closing nozzles (Ibid, p. 4-21). As of now there is no method of autonomously fueling manned or unmanned boats and craft in the U.S. Navy. However, interest is increasing as there has been at least one internal effort to investigate autonomous methods for refueling Unmanned Surface Vehicles (Galway and Phillips 2007), although very little published information on the subject exists.

It is important to note that in order for a process as complex as autonomous refueling of USVs to be accomplished, several things must be developed concurrently. First, the equipment and capability to send fuel from the host ship to a USV will need to be developed. Technology similar to this exists, but its use will involve development of new designs and modification of existing equipment associated with the internal components (tanks, piping, pumps). In addition to this known technology, the host ship will become the base for a yet to be developed connection device. Similarly, the USV will have to be fitted with internal changes to accept and transfer fuel internally.

Again, the technology exists but since USVs in general are still evolving, the priority of compatibility with a yet to be developed fueling concept among USV designers is low. Along with USV and ship changes, new equipment needs to be addressed. The equipment making the connection for towing between USV and host ship to hold the USV in position during refueling (such as a tether or robotic arm) needs to be developed. Along with this connection, an automatically sealing fluid transfer connection needs to be established. This is new technology and will require development of a lightweight and reliable automatic refueling connection with remote releasing capability. Equipment developed with the purpose of refueling USVs should take advantage of lessons learned from development of existing Naval refueling equipment. Towards this goal, a team consisting of experts from NAVSEA UNREP group of Port Hueneme, California, and NSWC CD S60 would make an excellent design partners with USV designers and host ship designers. These three items (USV changes, host ship changes, and new equipment) represent the three hardware legs necessary for a successful development of refueling at sea capability for USVs. While these hardware items are developed, software for the USV and host ship to enable autonomous operations will also need to be developed. Beyond that, the crew of the host ship will require training to properly monitor USV refueling operations and take control when needed in the process. Finally, the refueling system will need to work in conjunction with the launch and recovery system for the USV. A successful autonomous refueling system for USVs will require an awareness of concurrent on-going developmental efforts and a unified long-term developmental commitment from potential host ship developers, USV developers, refueling equipment developers, and the training community. The need for parallel development of several components, an awareness of present and future USV and ship integration needs, and vigilance in

program support creates some interesting project engineering challenges.

## **REFUELING CONSIDERATIONS FOR EXISTING USVs**

The first consideration for USV designers seeking autonomous refueling capability is compatibility with the host ship's USV connection method. Presently, the only host ship capable of an autonomous connection to USVs is the LCS, although others may follow. Autonomous connection is currently only planned as the first step in a recovery procedure, but would also be the first step in an autonomous refueling procedure. Currently, there are two autonomous recovery connection options for USVs, adaptation to the external latch mechanism design (such as the ASW USV) or adaptation to an integrated internal latch mechanism design (such as the MIW USV). Design considerations associated with these devices are detailed in reference 9. All other USV designs will need to incorporate similar latch mechanisms or develop a new type of refueling system that also has a latching system compatible with host ship recovery systems. Although there are many USVs currently in development, the autonomous launch and recovery equipment development is limited to a few practical designs (Coats 2006). The ability to incorporate one of the existing latch mechanisms or even a recovery concept already in development is a design consideration for next generation autonomous refueling designers. The launch and recovery methods being developed now may not be the final method used by USVs of the future, but the need for compatibility with the host ship will always be a requirement. If a concept cannot be developed for remote connection to the host ships, the USV will have to be recovered for refueling to occur. As new ideas come forth for autonomous refueling, it is important for designers to consider the impact to USV and

host ship, and cost of new equipment development in their planning.

Another set of design considerations involves study of the current refueling needs of the USVs, thus establishing a baseline for autonomous refueling system capability requirements. Using the ASW and MIW USV designs as a basis for development of autonomous refueling capacity requirements, the first consideration is the capacity of the fuel tanks. The range of fuel capacities is between 600-800 gallons. The maximum amount would be 800 gals, with a normal amount being about half that, or from 300-400 gallons. An interesting side note is that some USVs, including the ASW, operate in pairs, so from a mission perspective, two refuelings would be needed to return to a mission. A second characteristic is the existing tank design pressure for USV fuel tanks. The range for current tank test pressure is between 4.4 psi and 5.8 psi. All tanks are vented to air, with excess fuel going overboard if tanks are over-filled. A third consideration for refueling system design is the towing force required for each hull. This is relevant information because a hose passed between the host ship and the USV from the stern might have a catenary that will induce drag if allowed to contact the water as host ship and USV make headway. The only resistance that the USV can offer for festooning this hose from the tow line in a manner similar to the STREAM concept is coming from drag on the boat against the tow, unless USV engines were put in reverse. A tow connection at low speeds will have very little drag force on the tow line. Given the low freeboard of current USVs (3' or less), the amount of space available to prevent dragging the hose in the water is small. This would mean that the tension in a hose filled with fuel would have to be very high, the hose tightly festooned on a very high tow line, or designed such that the added force resulting from dragging the hose in the water is acceptable. The magnitude of this design consideration will be a function of the length of the tow. The acceptability of

dragging a hose in the water is an issue that will need to be investigated.

## **EXISTING/FUTURE HOST SHIPS AND FUEL SOURCES**

Although the refueling host ship for USVs is expected to be the LCS in the near term, other possible USV refueling ships and sources are a definite possibility. The current method for refueling an OOV, including USVs, is to bring them aboard the LCS, secure them, then refuel from a refueling station local to the recovery area. Specifically, the LCS had as operational requirements to provide JP-5 and DFM to the recovery area. The JP-5 shall be provided from a JP-5 fueling nozzle, with a high fuel rate, dry break capability, and automatic shut-off. Fuel is to be provided from separate systems rated at 15 to 60 GPM. LCS also has to provide a means for defueling USV, UUV and other boats in the sea zones. This process of refueling is simple and effective, but is not autonomous and has some limitations.

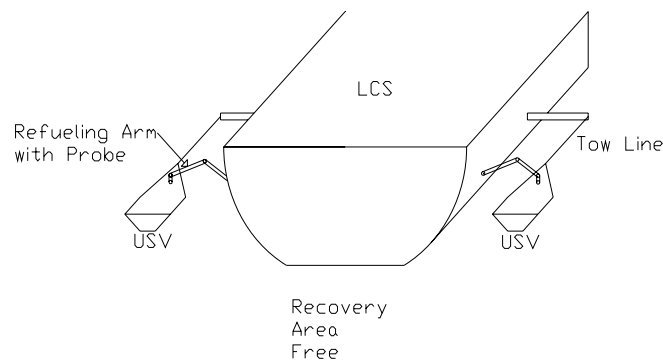
The biggest limitation of onboard non-autonomous refueling is the need to bring aboard any OOVs that require refueling, including USVs. While studies have shown that this process can occur in a matter of seconds with some systems (Sheinberg, Rubin, 2003) the requirement for LCS is that they must be able to launch and recover water craft in sea state 3 in a minimum of 45 minutes (Johnson et al, 2005). Due to the size (39', 22,600 lb) and complexity of autonomous recovery for some USVs, the expectation is that time required for recovery will use much of the allotted time. Add to this estimate the amount of time that 300-400 gallons of fuel can be optimally transferred to the USV, and it will take an hour for each refueling. A second limitation is the ability to service only one USV at a time. This limitation means missions with quick turnaround and the need for multiple USVs will automatically be delayed an hour for each USV involved while refueling

occurs. There is also the assumption that everything will go as planned and the crew on the recovery area of the LCS will recover, refuel and launch USVs as efficiently as the flight deck crew of an aircraft carrier might turn around aircraft. This will require reliable equipment, proper crew training and a bit of luck as there are unpredictable environmental factors involved and there is only a single recovery point.

Although the near-term host ship for USVs is the LCS, there are conceptually other sources of fuel for USVs. If common equipment can be developed that can be installed on other combatants or refueling ships, then they too could act as fuel suppliers for a USV. Development of equipment which could interact with existing UNREP equipment and practices would be the most cost-effective approach to such an endeavor. A second concept discussed is for development of a USV dedicated to the mission of refueling other USVs. This would present another challenge, a USV to USV autonomous refueling evolution. A third concept is to use a refueling process compatible with static equipment, such as refueling buoys or a floating docking station. Each of these concepts can extend the range of a USV and take the host ship out of the battle area. In the case of the static buoys, they could be arranged to enable USVs to travel great distances independently. Clearly, there is great potential for expanding the mission area and range of USVs from development of an autonomous refueling system.

Refueling multiple OOVs and USVs will be part of the mission of any host ship supporting a swarm. Although not part of any current design concept, providing more than one dedicated refueling area on a host ship would provide some capability for parallel refueling efforts and possibly offer additional refueling stations for refueling of manned boats away from the recovery area. As seen in Figure 2, one concept would involve flexible booms that swing out from the host ship at different locations (Galway

**FIGURE 2. Concept of dual side refueling stations for USVs**



and Phillips 2007). If these booms were fitted with the equipment required to capture and refuel a USV, there would be no need to bring the USV aboard for only refueling. Similarly, booms that had on them only refueling nozzles could swing out for OOVs to refuel in calm water or slow speed operations. One arrangement would have two forward booms for OOVs, two aft booms for autonomous USVs, and the stern ramp left open to recover any OOVs as needed. As an added measure of safety, a temporary inflatable fender could be installed during operations to prevent unwanted collisions between the USV and the host ship while the USV is tethered.

## **DESIGN CHALLENGES, CONSTRAINTS, AND CONSIDERATIONS**

It is impossible to focus exclusively on the refueling challenges without mentioning first the challenge associated with launch and recovery of USVs at sea. A connection between host and USV is necessary in any refueling endeavor. It is not essential that a connecting device be capable of autonomously launching and recovering a USV if the USV can be held in a fixed position relative to the refueling host ship long enough and stable enough to permit other equipment to refuel the USV. An example of this arrangement would be

capturing a tether line using the latch mechanisms under development and being in-hauled to a refueling boom where a robotic arm would reach down and make a fuel connection. In this manner, the USV could be re-fueled without needing to come back aboard the host ship.

All refueling concepts need to address the same initial design consideration, relative motion between ship and USV. The ability to conduct operations in various sea conditions is a typical design constraint that has the potential to drive up the cost of any launch and recovery or refueling equipment. It is an LCS mission goal to operate in various sea state 3 conditions and a long range goal for ONR R&D to look at operating in higher sea states. Relative to the design of new equipment, a sea state provides a way of quantifying the probabilistic conditions of the ocean during operations with wave and wind statistics. These statistics are applied to the physical characteristics of a craft or ship to in turn create a set of corresponding dynamic conditions at points of interest on the craft, usually where new equipment will be located. Design engineers typically design an item to survive the worst case, so if a design goal of operations in a particular Sea State were desired, all factors of safety would be applied to the conditions at the worst case leading to very conservative

designs for the majority of the operations.

Complicating things further are some relative motion issues. When two objects with a large mass (such as a ship and a craft) conducting a mission that puts one dependent of the motion of the other, and both are subjected to a significant sea state, the resulting range of possible relative dynamic conditions is large. In the case of refueling, there needs to be both an initial connection of some kind made and a subsequent tow initiated. The dynamic conditions will influence the ability of the initial connection to be made and the magnitude of forces passed between any connecting link. Another factor that should be considered in any discussion about the effect of sea state on small craft is the understanding that because of the relative size difference, the sensitivity to swells and waves will be different between the ship and the small craft. Since there are various scales for measuring waves, Table 1 (Pierson,1964) is provided for some comparison in this study. While the ship will be able to plow through sea state 2 & 3 relatively easily, its pitch motion will tend to have a large

periodicity relative to the smaller craft; however, the vertical distance change caused by swells at the stern of the ship may be substantial. A USV will tend to follow waves that are of a longer period-as are big ocean swell with periods of 10 to 20 seconds. Shorter waves, of approximately 1 second period, will result in little pitching as the frequency is faster than the natural pitch frequency. Waves that are close to the resonant pitch frequency will cause large pitch amplitudes, and result in the boat getting out of phase which is manifested by the bow coming down as the sea surface rushes up with the next wave resulting in slamming/pounding. It is also worthy to note the freeboard of USVs will be in the 2-3' range. If the combination of wave height and frequency is right, the bow may be pitched down into an on-coming wave causing it to break over the bow. In the situation where the small craft is being towed, the towing force will try and force the bow of the boat through the wave, substantially increasing the load in the towing gear. The sensitivity of the small craft to the wave effects is further amplified by the speed at which the craft is traveling.

**TABLE 1. Sea States from NATO Standard Agreement (SNAME,1989)**

Sea State	Sustained 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

There are also several hardware design considerations relative to autonomous refueling of USVs that are new and unique to the passage of fuel. Perhaps the largest consideration is the need to maintain a good seal between connection halves. Although achieving and maintaining a seal is nothing new in refueling systems, the equipment required to accomplish this autonomously demands that the force required to seal come from some other source besides a human.

Alternative methods of providing this force include active methods, such as an electrical, hydraulic, or pneumatic interlock, or passive methods, such as using the propulsive or drag force from the USV or gravity to make the seal. Active sealing methods are perhaps more positive, but there is a complexity and weight penalty for the actuation device and the power source unless the power can be transmitted from the host ship. Sealing is coupled with another design consideration,

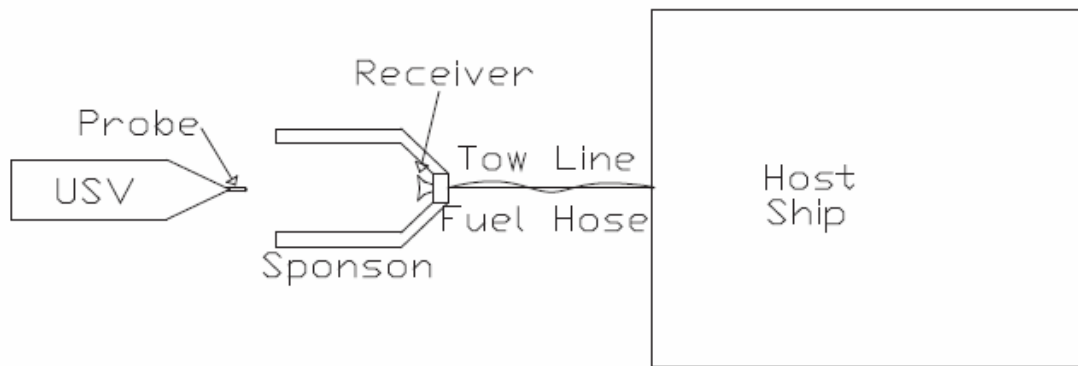


amount of spillage and risk of major spills. Any refueling-at-sea evolution will have a minor amount of spillage. Whether the spill is a few drops that hit the deck and find their way into an overboard drain or an emergency break-away or hose rupture, there exists some risk of spill. Current Naval operations minimize the risk in many ways, one of which is blowing down the lines prior to transfer, minimizing the fuel available for a spill after decoupling. The size, availability, weight and complexity of such a system would have to be balanced against the value added in reducing a spill for such equipment in an autonomous refueling system. Nevertheless, the environmental and political risks associated with a spill are high for craft operating in littoral waters. Prior to fielding any autonomous transfer method, testing and risk assessment will need to occur and be approved by environmental regulating bodies. Another consideration is the need for an emergency breakaway procedure that allows USV and host ship to part quickly, retain the gear required for later refueling and take emergent or evasive action as circumstances warrant. The emergency break-away procedure will impose design considerations such as potential for fuel loss and automatic resetting for later operations. A fourth design consideration is the need to develop refueling-at-sea equipment that is of a size more conducive for fuel transfer to USVs. The smallest size equipment in the current naval refueling-at-sea inventory is 2-1/2" diameter. Relative to the amount of fuel being transferred and the size of the craft involved, this size seems excessive and precludes use of the existing U.S. Navy ship refueling equipment. Current refueling of boats is accomplished with 1-1/4" equipment, but this is manual and similar to what might be used at a marina. As a side note, the Coast Guard uses 1-1/2" refueling equipment for refueling helicopters that might be considered for us in refueling the USVs (Galway & Phillips 2007). Hose of this size should be able to deliver between 600-800 gallons of fuel in 20-30 minutes with less than 10 psi pressure drop in 100'

of hose (Ibid). These operational parameters fall into the range of what might be expected during a USV autonomous refueling. A fifth design consideration is the location of the refueling equipment on the USV. Current concepts use the front of the USV forward of the collision bulkhead as the area most likely to be the autonomous refueling transition point. Putting refueling equipment in this location adds the potential for fuel to be involved in any collision involving the bow. The ability to do this and have it approved by USV design regulating authorities might pose a significant administrative challenge, but since USV technology is emerging efforts to redefine design regulations for unmanned craft should be a possibility. A final consideration is maintaining the quality of the fuel during transfer. Having water enter the fuel system during fuel transfer would put the immediate mission in jeopardy and if the USV comes back to the host ship to be de-fueled, might lead to contamination of a larger tank of fuel. This concern is associated with the quality of the seal. Current naval refueling operations include taking test samples of fuel being transferred. All the identified refueling design considerations are in addition to the design considerations associated with launch and recovery. Individually, there is not one challenge so technologically advanced that it can not be solved with today's technology. Collectively, these challenges form a design goal for an autonomous refueling system for USVs that can only be achieved by a cooperative development effort by USV, ship refueling at sea, and UNREP equipment designers.

## **DELIVERY CONCEPTS IN DEVELOPMENT**

NSWC CD Code 23 has two concepts for accomplishing autonomous refueling of USVs from a host ship. Both involve a towed sponson approach for USV refueling and use a probe/receiver/sponson connection method rather than a line catching recovery

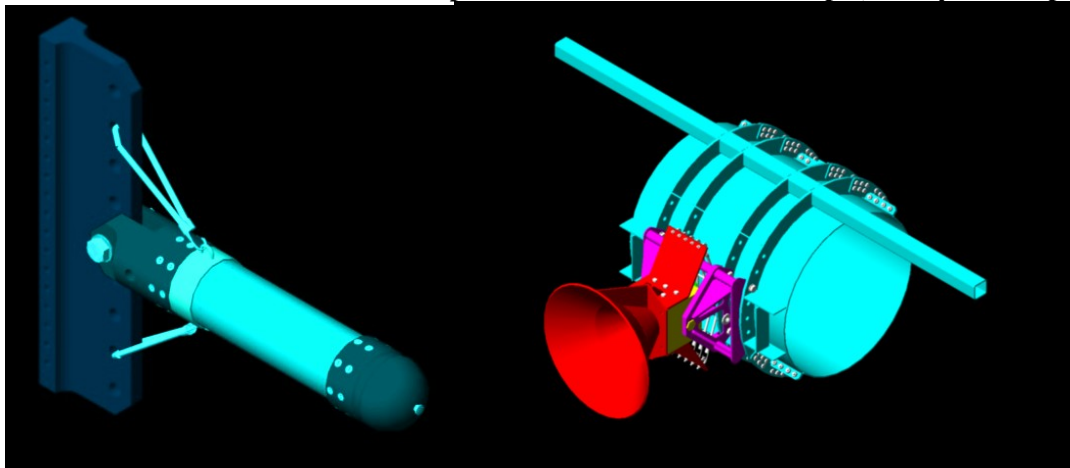


**FIGURE 3. Plan view of the Probe/Sponson/Receiver concept of Refueling**

method. A probe and receiver similar to the current air-to-air system would be used for this approach to refueling, only designed for use on the water. While water use would be at a slower speed, the water surface effects create many additional challenges. As seen in Figure 3, a floating sponson, similar to the outside flotation collar on a RIB, is towed off the stern of the parent ship with a tow

line and a refueling hose connected from the ship. At the sponson the hose connects to a receiver, similar to that seen in aircraft refueling. However, instead of having the USV maintain speed, as in the case of an areal refueling, the USV then is brought under tow within the sponson by the probe connection and refueling can commence (Figure 4).

**FIGURE 4. USV mounted Probe and Sponson Mounted Receiver Concept (Galway & Phillips 2007)**



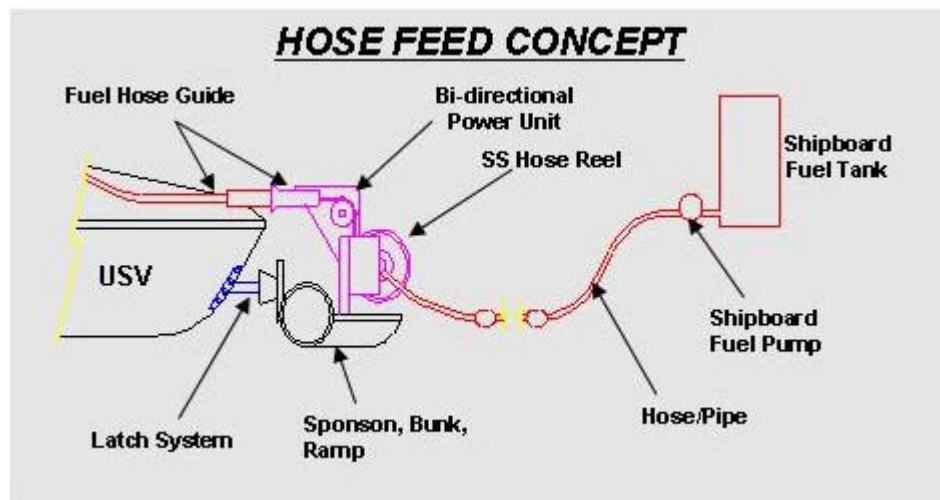
After refueling is complete, the USV signals the sponson to release, then the receiver disengages the probe, and after the sponson is pulled clear by the host ship, the USV is free to pull away. The floating sponson can also serve to guide the USV into place until the probe of the USV mates with the

receiver mounted on the floating sponson. In theory, when the boat is in position in the sponson, the vertical motion between sponson and boat is expected to be reduced since they are both in the same relative position to the waves and should react similarly to them. When the probe locks

into the drone receiver, the USV is brought under tow and refueling from host ship can begin. Upon completion of refueling, the USV signals the probe to release and return to a retracted position. The USV can then return to its mission without needing to be recovered aboard the host ship. The primary advantage of not coming aboard the ship is reducing the time spent refueling, but an additional benefit is reducing the risk of damage caused by recovery. Development of a probe as the primary connection method is currently underway as part of an effort NSWCD Code 23 is accomplishing for ONR Code 33. Concept development of a follow-on probe/latch that enables the transfer of fuel is underway in a parallel effort.

A second concept being developed by NSWCD code 23 is the hose feed concept as shown in Figure 5. This method again uses a sponson & probe connection method, but has an additional set of small powered capstans also mounted to the sponson such that a refueling hose can be pushed between them. Upon connection between sponson & USV, these powered capstans push hose from the host ship into a fixed conduit on the USV until the hose snakes down into the USV tank. When the hose is in position, fueling can commence. This method is very basic and has limited impact on the USV. It relies on a hinged gate valve, gravity and drain hole position to prevent water from intruding into the fuel tanks during normal USV operations.

**FIGURE 5. Hose Feed Concept of Refueling**



An undeveloped but promising third concept involves the combination of a robotic arm or boom. An articulating arm or boom sensitive enough to capture the USV, strong enough to hold it in position, and then capable of making a fuel connection would be a compact way of accomplishing the refueling mission. This form of refueling concept might also lend itself to multiple refueling stations discussed earlier. Some of the barriers to this type of concept include building an arm strong enough to take the

loads associated with towing a 22,500 lb USV, developing a sensor system capable of performing the function of connecting a refueling device in an extreme marine environment, and integrating this type of concept into the host ship. While this technology is attractive, it is not yet far enough along the development curve to be a contender for installation on the current host ship designs.

## CONCLUSIONS

A key parameter in the success or failure of a single host ship deploying and supporting multiple OOVs and USV will be its ability to rapidly provide them support during extended operations, including refueling. As USV size and the desired operational sea state increases, the complexity and risk associated with recovering USVs and OOVs at sea will also increase. A method for autonomous refueling without recovery of a craft at sea has the potential to reduce overall refueling time and allows for possible multiple refueling simultaneously. Development of all aspects of this technology in parallel (USV, ship, equipment) is a way to mitigate the risk of host ship exposure during refueling operations and potentially keep it away from a combat area altogether, thus allowing for more response time to hostile threats. Reducing the number of required launch and recovery evolutions at sea also reduces the risk of damage to USV and host ship as well as risk to personnel involved in the recovery effort. Continued development of this technology as a means to reduce and mitigate risk for the future LCS fleet is warranted and recommended.

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