2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
Congress Center Hamburg
Sept 28 - Oct 2, 2015. Hamburg, Germany

Autonomous Robotic Refueling of an Unmanned Surface Vehicle in Varying Sea States*

Gregory P. Scott, C. Glen Henshaw, Ian D. Walker, *Fellow, IEEE*, Bryan Willimon

Abstract—**In an effort to improve sailor safety during underway replenishment on the open sea, a robotic refueling system has been developed to autonomously refuel unmanned surface vehicles (USVs). The Rapid Autonomous Fuel Transfer (RAFT) project has demonstrated a methodology that could be used on the open water to autonomously refuel Navy vessels at significant sea states. The prototype refueling system is made up of two robotic arms: a rigid and precise industrial robotic manipulator to pinpoint the location of the target fuel tank and a novel soft pneumatic arm (Octarm) to provide compliant and safe contact with the USV. At the end of the Octarm, a magnetic end effector was designed (patent pending) to transfer a refueling "puck" from the robotic system to the target fuel tank. Acting under manual control or autonomously through visual tracking techniques, the robotic refueling system was shown to effectively transfer fuel to the target US Navy Sea Fox vessel under sea state 3.25 conditions at the US Army Aberdeen Test Center. The results demonstrate the feasibility of using a robotic solution to allow autonomous shore-to-ship or ship-to-USV refueling. It also illustrates the benefits and challenges of future robotic ship-to-USV refueling operations. This represents the first demonstrated use of a robotic system for fluid transfer to vessels in active sea states. This paper describes the design, development, and demonstration of the prototype autonomous refueling system.**

I. Introduction

Refueling Navy vessels in the open sea, as with all underway replenishment (UNREP) activities, is a challenging prospect. Large, conventional vehicles require huge cranes to hoist the required fuel lines and associated cabling between two vessels during a connected replenishment (CONREP). Sailors are in the loop to manually attach and detach all of this required cabling and react in case the process does not go according to standard operating procedures. If the ships veer too far apart or communication breaks down during the process, lines can violently snap and sailors can be injured or killed. As the weather conditions worsen and the sea states (wave height, period, and power classification defined in more detail in TABLE I.) grow more challenging, the risk to the crew also grows. Fig. 1 gives an overview to a refueling UNREP activity and also shows the refueling probe used to transfer fuel between ships.

*This research was funded by the DARPA Tactical Technology Office under the Rapid Autonomous Fuel Transfer Seedling Program and the U.S. National Science Foundation under award IIS-0904116.

G. P. Scott, PhD and C. G. Henshaw, PhD are robotics researchers with the Naval Research Laboratory, Spacecraft Engineering Department, 4555 Overlook Ave., SW, Washington DC 20375.

I. D. Walker, PhD is a Professor in the Department of Electrical and Computer Engineering, Clemson University, Clemson, SC 29634.

B. Willimon, PhD recently completed his PhD research at Department of Electrical and Computer Engineering, Clemson University, Clemson, SC 29634.

For unmanned surface vehicles (USVs), the difficulty of successfully achieving this task on the open water is even more significant. These smaller vehicles are more significantly affected by the open water sea state and are not as stable in these waves as larger vessels. Additionally, there are no sailors on board these vehicles to assist in the refueling process. Therefore, a significantly different approach must be considered to refuel these vehicles and get them back out on their mission as efficiently as possible.

Various underway replenishment techniques are currently used to refuel USVs on the open sea [5]. Some USV refueling techniques require the smaller unmanned vehicles being captured by the fueling ship and hoisted on desk to refuel. In other cases, a sailor is hoisted overboard from the refueling vehicle by a crane and manually attaches the fuel lines to allow the fuel transfer. These techniques are either exceptionally time consuming or put the lives of sailors in jeopardy – neither of which are favored in any circumstances, particularly during an active mission.

A solution must exist to enhance sailor safety during replenishment activities by removing him/her from the refueling process altogether. However, currently "there is no method of autonomously fueling manned or unmanned boats and craft in the U.S. Navy" [5].

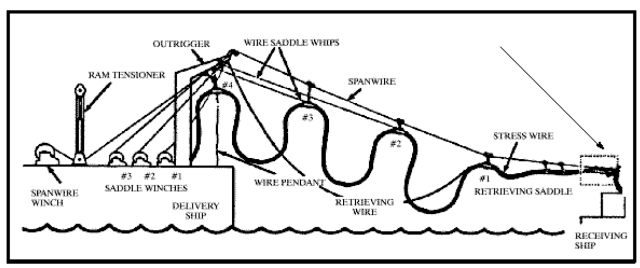

Fig. 1. An example of UNREP refueling between the delivery ship and the receiving ship [13].

In order to address these existing issues with refueling USVs, a team proposed a cost effective, time-efficient, and sailor-safe robotic refueling solution. This team consisted of the Space and Naval Warfare Systems Command (SPAWAR), the Science Applications International Corporation (SAIC), the Naval Research Laboratory (NRL), and Clemson University. Each organization focused on a different area of the challenge. This paper addresses the feasibility analysis, design study, and initial conceptual prototype of a robotic refueling system through development, control, and testing, which was the primary focus of the NRL and Clemson. The topics of wave modelling, wave prediction, and hardware advancement to a fielded system are not covered in this paper.

II. CONCEPT AND APPROACH

A. Design Approach

In order to address the challenging issues involved with refueling USVs, the team proposed a robotic system that could be controlled both manually by sailors onboard the refueling vehicle or autonomously through visual tracking of the target refueling receptacle. This robotic system would be made up of two primary mechanisms: a rigid industrial manipulator and a compliant pneumatic manipulator. The rigid industrial manipulator would provide a rapid and pinpointed movement and will respond quickly while tracking the movement of the location of the fuel tank on the USV. The compliant pneumatic manipulator would provide a soft and flexible connection between the rigid arm and the fuel receptacle in order to minimize the chances for damage to either arm or the vessel while allowing flexibility to the connection during wave-influenced motion.

B. Robotic Components

The robotic components for this Phase I project were selected based on the in-house robotics capabilities of the leading robotics institutions performing this task. As such, the Mitsubishi PA10-7CE industrial robotic arm (Fig. 2) was selected as the rigid arm hardware, in part due to this model being regularly used by the NRL for various prototype robotics projects. Additionally, the Clemson-designed Octarm [9] was baselined as the pneumatic compliant robotic arm (Fig. 2). Each of these arms and their supporting infrastructure will be detailed in the following sections.

1) Mitsubishi PA10-7CE

The Mitsubishi PA10-7CE industrial manipulator was selected to be the backbone of the robotic refueling system. The NRL has been using the PA10 model robotic arm for several years for numerous early-phase research projects including coordinated dual-arm satellite servicing demonstration tasks and autonomous grappling [2].

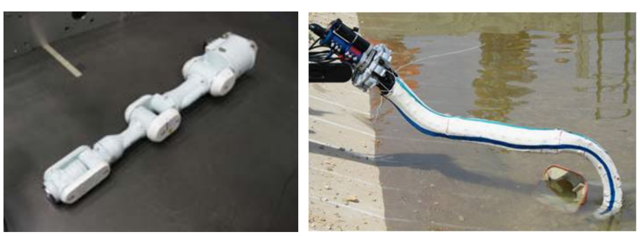

Fig. 2. The Mitsubishi PA10-7CE and the Clemson University Octarm.

It is a seven degree-of-freedom robotic manipulator with a workspace of up to 1 meter from the base and a maximum load capacity of 10 kg [11]. The PA10 is also a fast moving robotic manipulator. With operating speeds of 1 rad/sec for the base joints and 2π rad/sec for the wrist joints, the arm can quickly respond to an ever-changing maritime environment. It also has sub-millimeter accuracy to ensure precision placement of each joint and the end effector location. Furthermore, utilizing individual joint torque control allows for dynamic control algorithms to be incorporated for greater flexibility in the overall arm movement.

2) Octarm

Mounted at the end of the PA10, and acting as a “tongue” for the system, is a continuous backbone “continuum” manipulator called the Octarm [12]. The Octarm is a compliant system inspired by octopus arms. Pneumatically driven, the Octarm is formed directly from the McKibben muscles (air tubes constrained by external braiding) which actuate it. These muscles are arranged to form a backbone of three three-degree of freedom sections. Each section can extend and contract along its length and bend in two dimensions, for a total of nine degrees of freedom. The Octarm has unloaded weight of 15 pounds and nominal length 42 inches, with payload capacity 22 pounds (~10 kg). It was developed primarily as a manipulator, and demonstrated to grapple or manipulate of a wide variety of payload shapes, sizes and masses [4][7].

The key property of the Octarm exploited in this project is its inherent ability to mechanically comply safely with external loads. Compliance in the overall robotic system is critical for successful refueling, as non-trivial sea states will inevitably create un-sensed/unpredictable relative motions between the refueling system and boat. These motions lead to (at times fairly violent) impacts and collisions between USV and refueling system. In a rigid robotic system, these impacts result in high internal forces, compromising the structural integrity of both systems. Thus a compliant link in the robot system is highly desirable.

Continuum robots are inherently dual to conventional manipulators, in the sense of featuring low precision but high compliance [7][13][15]. This makes them good candidates for robotic operations involving unpredictable contact and impact. However, to date there have been very few practical applications of continuum robots [3], and those involve relatively slow and/or mostly non-contact operations [14]. The application developed for this project is believed to be the first fielded application of a continuum robot exploiting its ability to adjust to significant contact and impact dynamics. Additionally, relatively few continuum robots have been designed for [1][6] or operated in [8] dynamic aqueous conditions prior to this program.

3) Combined system

Together the PA10 and the Octarm make up the robotic refueling system. This system has a total reach of nearly 2 meters when controlled to its longest reach position. In total, the system has 7 rigid degrees of freedom (from the PA10) and 3 pneumatic segments with 3 degrees of freedom in each (from the Octarm), totaling a 16 degree of freedom system.

In between the PA10 and the Octarm is an aluminum camera boom with a down-pointing digital video camera. The uEye 1225LE USB camera provides a resolution of 752x480 pixels and is fixed on the boom to provide the input to the visual servoing subsystem. Visual servoing involves the tracking of a target and adjusting the movement of the robotic system based on that changing target location. This camera is tracking the location and orientation of a square fiducial, at a rate of 15 Hz, which is the maximum frame rate that the camera will allow. The camera is located a known distance away from the refueling receptacle and locked into place. The imagery is then fed into the visual servoing system to control the robot and the arm controller is running at 400 Hz to accurately move the robot to the target. The tracking rate of the camera and the response rate of the visual servoing controller is expected to have sufficient bandwidth to track the movement of the fiducial based on the impact of the sea state and will be validated during the initial demonstrations. The robotic arm is autonomously moved to pinpoint the end effector overtop of the fuel receptacle so that the end effector can attach to it and transfer fuel.

The overall robotic refueling system is controlled through a flexible user interface. This interface allows the user to select joystick-control to manually control the system or autonomous tracking of the fiducial and refueling receptacle. The user interface includes a window with the video camera display, a real-time analysis of the location of the fiducial with respect to the fuel tank, and the position and orientation of each joint of the robotic arms.

C. Supporting Infrastructure

In order to effectively test the robotic refueling system, a supporting infrastructure was developed. This included physical supports to mount the robotic system to the wave tank walls, a target refueling receptacle, the end effector fuel transfer system, and the boat on which the refueling would take place. Each of these elements is detailed in the following sections.

1) Adjustable Mounting Truss

An adjustable mounting truss was designed and built to support the robotic refueling system and is illustrated in Fig. 3. This truss was mounted on the wall of the wave tank at the US Army Aberdeen Test Center (ATC) to extend the robotic arms over the boat as it approached the side of the tank. The truss was designed to be adjustable in three directions but was locked into place for the tests. It could shift the robotic arms outwards further into the water (or closer to the wall), the height was adjustable to ensure the end effector could reach the USV fuel tank, and it could also be shifted horizontally along the wall. During implementation, the horizontal mounting brackets were deemed unnecessary for the tests and were not mounted to the wave tank for these tests.

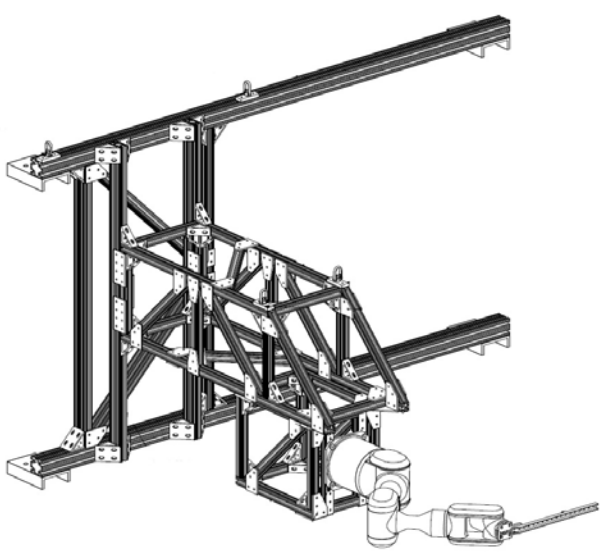

Fig. 3. Diagram of truss structure to hold the RAFT Robotic Arm System

2) Refueling Receptacle

A refueling receptacle was designed as the target for the end effector to attach to in order to transfer fluid onto the USV. The receptacle is made up of a tank to store the transferred fluid, the fiducial which is required by the robotic arm visual servoing system, and the docking interface where the robotic arm end effector attaches to transfer fuel.

Several iterations were completed prior to implementing the final design. The initial concepts included building a funnel to ensure the end effector would be directed to the docking interface. It was soon realized that this caused the Octarm to become caught up in the funnel and not directed to the docking interface. Additionally, it was determined that the PA10 and Octarm control together were sufficiently accurate to target the docking interface. When the funnel was removed, other aspects of the built platform were also obstructing the Octarm movement, causing interference or undesired magnetic attraction to some of the ferrous bolts holding the system together.

In the final version of the refueling receptacle, a thick plexiglass sheet was selected as the base of the refueling receptacle. This allowed not only a flat non-ferrous surface, clear of any obstructions or magnetic attraction from the end effector, but also allowed the research team to view when the fuel tank was being properly filled by the fueling mechanism. The fiducial was placed on the plexiglass and the control system was programmed with knowledge of the relative distance and orientation of the fuel tank from this fiducial. The final system is shown in Fig. 4.

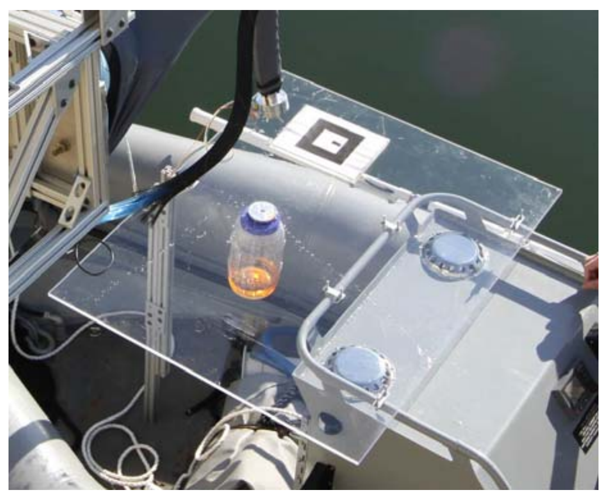

Fig. 4. Final refueling plate design of the refueling plate.

3) Fuel transfer "puck"

The fuel transfer system was designed and prototyped to transfer fuel through a robotic arm from a host refueling ship to a target fuel tank on an unmanned surface vehicle (USV), without the need for direct human intervention. The robotic arm component was designed to target the fuel tank and get the end effector close to the fuel receptacle where magnets in the puck would then automatically attract and align with the target fuel tank. The compliant Octarm component was designed to be sufficiently compliant in nature to ensure neither the target nor host systems were damaged during rough seas.

The fuel transfer system provides a self-aligning magnetic connection between a host system and a target system. In the first and second generations of this development, the magnets connected directly between the host system and the target system and transferred the fluid without allowing for disconnection in the case of significant position shifting. This method proved to be inadequate due to the significant changes in relative position of the target and host systems due to the waves encountered by the USV in the open water, which would pull the magnetic end effector away from the target (spilling fluid in the process). Therefore, a more robust method was developed to include the fluid transfer "puck", which resulted in the third generation device, shown in Fig. 5.

Fig. 5. The magnetic end of the Octarm with the final generation designs of the refueling end effector.

Within this self-aligning magnetic connection is a transferrable "puck" that has a magnetic connection that is stronger towards the target system than the host system (alternatively, electromagnetic connections can be used to control the connection strength as desired by the operator, but this approach was not evaluated during this program). This magnetic connection differential allows the puck to connect to the target system and, in the case of a jolt in the system, the magnetic connection is released by the host system while the puck maintains connection with the target system. In the final prototype of the invention, the puck would need to be manually removed from the target system or pulled by a safety support cord to dislodge it from the USV magnet. Fig. 6 shows the process by which the puck is mechanically transferred from the end effector of the Octarm to the fuel receptacle, demonstrated in the lab.

The puck was also designed as a fluid transfer system. Although the magnetic connection mechanically held the system together, an additional flexible hose (not structurally supporting) was connected through the puck. This hose was used to transfer the fluid between the host system and the target system. In the event that the magnetic connection was lost, the flexible hose has sufficient slack in the line to allow it to be unaffected by drastically shifting distances between the target and host system. Fig. 6 shows a close-up of the third generation prototype of the puck itself, with the yellow quick disconnect connector for attaching the fluid transfer line.

With this design, the puck would remain connected to the Octarm end effector while the arm was approaching the target fuel receptacle. When contact was made with the target, the stronger magnet would keep contact with the target magnet. If the waves became too high or the boat moved out of the range of motion of the refueling system, magnetic contact with the host system would be lost (due to the weaker connection here) and the puck would be transferred to the target fuel receptacle. Fuel can still be transferred in this semi-detached configuration, and the puck can be mechanically retrieved when refueling is complete.

4) US Navy Sea Fox Vessel

A US Navy Sea Fox was acquired for use on this project. The rear platform assembly was folded down and out of the way, as none of the associated sensors were being used for this demonstration and a fuel receptacle mockup was built and mounted to the front, as shown in Fig. 7. This could be reached by the robotic refueling system, which was mounted to the truss and extended over the water.

Fig. 7. The US Navy Sea Fox used as the USV in this research at the US Army Aberdeen Test Center wave tank.

To reduce risk of contamination of the wave tank water, real fuel was not transferred between the robotic refueling system and the Sea Fox. Instead, dark colored water was transferred so that the fluid could be seen in the tank mockup during refueling.

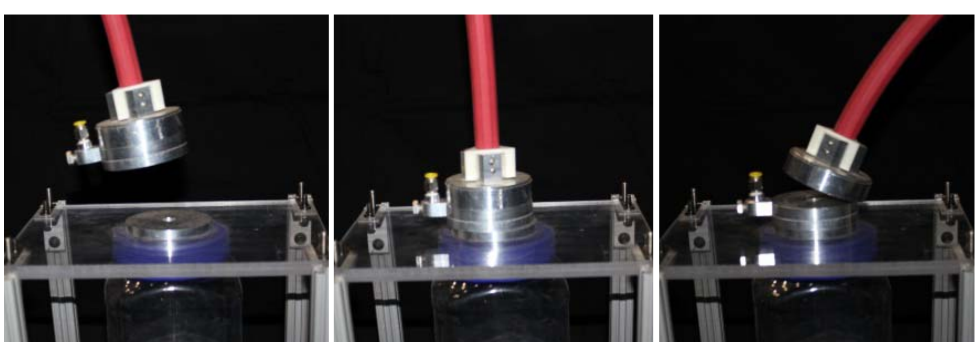

Fig. 6. Final refueling mechanism prototype mechanically transferring from a) the end of the Octarm to b) the fully connected state to c) the completed puck transfer to the fuel receptacle with Octarm disconnection.

III. Implementation and Demonstration

A. Initial System Testing

Prior to wave tank testing at the US Army Aberdeen Test Center, the team focused on the development and testing of the technologies required to perform each task of the project. This included the integration of the robotic arms, end effector targeting, visual servoing, and target tracking subsystems in order to perform fluid transfer.

Each individual sub-system was tested within their respective laboratories prior to full system integration. The Octarm control routines were tuned at Clemson University while the PA10 control algorithms were developed at the Naval Research Laboratory to include the visual servoing and target tracking algorithms. The first set of integrated tests took place in the Space Robotics lab at the Naval Research Laboratory. The first generation of the magnetic refueling end effector and the fuel tank mockup were developed for these initial tests.

The results following these initial tests showed that the robotic arm system could track the location of the fuel receptacle. It was also determined that the methodology used to dock the end effector with the fuel receptacle was insufficient and the receiving cone on the target was more often a hindrance than a help to the docking process, given the projected motion of the Octarm. Additional refinement to the docking procedures and the movement of the Octarm was required.

B. Sensing/Visual Servoing

The team developed a visual servoing technique to track a fiducial that was mounted a specified distance from the fuel receptacle, equivalent to as the distance between the camera mounted on the boom and the center axis of the Octarm. The process that was followed for tracking the fuel tank position is defined below:

- Capture new image frame from the camera.
- Process image to locate the fiducial and compute the position/orientation of the fiducial relative to the camera when it is found.
- Send fiducial position/orientation through a low-pass filter.
- Transform filtered pose data from camera reference frame into the refueling tool reference frame.
- Compute the error vector by comparing this observed pose to the desired pose.
- Multiply this error vector by a gain value (tuned during prototype testing) and then restrict it in a way that prevents large accelerations.
- Update desired tool position by adding the clamped error vector to the previous desired tool position.
- Restrict the updated desired tool position to be within the workspace limitations of the robot arm system to avoid joint limits and singularities.
- Use an inverse kinematics solver to compute new desired joint angles to move the robotic arm toward the desired tool position.
- Send new joint angles to the robotic arm.
- Repeat the above steps at every image frame.

Utilizing the above general procedures, the team developed a methodology that would accurately track the fiducial (and thereby the fuel receptacle location). Synchronizing the frame rates of the camera (15 Hz) and the error vector determination (400 Hz) proved a challenge, but the results show that this concern was successfully mitigated.

The visual servoing algorithm was based on ARToolKit, a popular open-source library intended for use in building virtual reality applications. ARToolKit includes very stable and robust fiducial tracking algorithm and is capable of reporting complete 6-DOF pose with respect to a fiducial at high frame rates. It works over a wide variety of lighting conditions, as well as being robust to light rain. Qualitative testing at the test site showed the fiducial tracking algorithm to be capable of reliably tracking the fiducial across all expected lighting conditions, which ranged from heavy overcast skies to direct sunlight, without requiring auxiliary lighting.

Fig. 8 shows the X, Y, and Z offset of the tracking fiducial from the camera during three consecutive laboratory runs. In the first run, the results show that the arm reaches from an average of ~1.7 m between the camera and the fiducial to 1.06 m separation. This shows that the Octarm is extended nearly 0.7 m to reach the current position of the fiducial (based on the boat's location in the waves). In the second run, however, contact was made with the camera 1.29 m above the fiducial, requiring an Octarm extension of only 0.4 m from its average position.

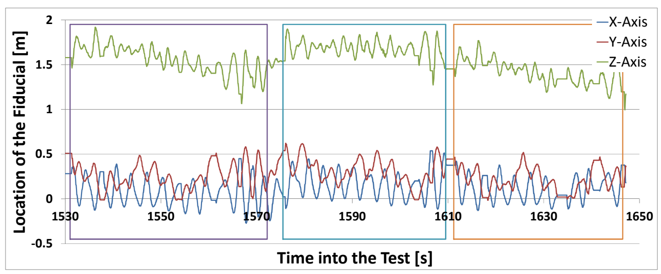

Fig. 8. Location of the tracking fiducial displaced from the robotic arm on three consecutive runs during the initial test demonstration.

C. Wave Tank Test Setup

In preparation for the testing at the Aberdeen Test Center, the equipment had to be accurately installed in place at the wave tank. The first step was installing the truss segment into the wave tank. In the initial attempt to do so, the structure was found to be too tall to allow the Octarm to reach the Sea Fox deck. Therefore, some on-site modifications to the structure were made in the field and the system was adapted to work as required to achieve the project goals.

Following the successful structural support modifications, the PA10 and Octarm were integrated with the truss and hoisted off the back of a truck and over the wave tank water, as shown in Fig. 9. Engineers on a servicing boat in the water then bolted the truss in place using an existing support infrastructure within the 9 foot tall concrete wave tank walls.

Following the complete installation of the truss assembly to the wave tank wall, the Sea Fox was moved into its proper location under the robotic arm system. The Sea Fox was unpowered during the entirety of these tests and therefore was craned over the wave tank wall in a manner similar to the truss structure. Once lowered onto the water, the boat was secured into place using nylon rope stretched to each corner of the wave tank (with attachment points front-left, frontright, back-left, back-right), as shown in Fig. 10. This would allow the boat to move with the waves, but restrict that movement to an area within the robotic arm workspace.

Fig. 9. The truss assembly integrated with the PA10 and Octarm and mounted to the wave tank wall.

Also shown in Fig. 10 is an enclosed structure on the platform above the robotic arm truss. This ISO container houses the robotic arm control system hardware and the software operators. Cables run directly to the arms provide the data and power transfer to these systems. Command and control operations took place in this structure to keep the hardware protected from the environment and so that the operators were unable to directly observe the ongoing operations and were therefore required to use the data transmitted to their control consoles.

Fig. 10. The US Navy Sea Fox in the ATC wave tank, secured in place to prevent the vessel from moving outside of the test area.

D. Test Procedures and Results

Three different test series were conducted with the complete system at the ATC – preliminary on-site evaluation, the full integration test, and the final refueling demonstration to DARPA. The key goals of the tests were to establish: (1) how effectively the system could mate with and transfer fluid to the USV; and (2) evaluate the system under increasingly challenging sea state conditions (repeatably created by the wave tank system).

1) Preliminary On-site Evaluation

The primary purpose of the preliminary investigation was to evaluate the overall system operation and capabilities. No formal data was collected for detailed analysis, but all systems and procedures were tested to ensure successful operations and to troubleshoot operational problems that would arise.

The results of the preliminary tests showed that many of the systems worked effectively, while others required updating and modification prior to the full integration test. The visual servoing and target tracking was shown to effectively detect the location of the fuel receptacle. The robotic arm system was also able to follow the movement of the fuel receptacle. Both of these were strong successes of the full systems integration test.

However, the movement of the Sea Fox due to the wave motion would often push the fuel receptacle outside of the robotic arm workspace area, therefore making tracking it impossible. A more effective solution to limit the x-y range of motion of the boat (while still allowing movement in the z-direction with the wave motion) would need to be developed.

2) Full Integration Test

The full integration tests occurred in March 2011 at the Aberdeen Test Center. These were conducted with the USV under five different sea state conditions, from calm (glassy) water at sea state 0 to sea state 3.0 with waves over 1 meter. Sea states higher than 3.25 were not considered, as they took the boat to the edge of the robotic arm system's range of motion. Waves were generated with both periodic and random wave motion. TABLE I. shows the Douglas Sea Scale in reference to estimating the sea state conditions considered in this test [10].

TABLE I. DOUGLAS SEA SCALE SEA STATE METRICS

Sea State	Height (m)	Description
0	No waves	Calm (Glassy)
1	0.00 - 0.10	Calm (Rippled)
2	0.10 - 0.50	Smooth
3	0.50 - 1.25	Slight
4	1.25 - 2.50	Moderate
5	2.50 - 4.00	Rough
6	4.00 - 6.00	Very Rough
7	6.00 - 9.00	High
8	9.00 - 14.00	Very High
9	14.00 +	Phenomenal

The Douglas Sea Scale was devised in the 1920s as a standard designation of surface roughness on the open seas. Although sea state 3 is delegated as "slight" wave motion on this scale, this is rather significant for vehicles of smaller sizes, including USVs. In these tests, the relative wave motion compared to the robotic systems used in this program is significant. The 1.25 m maximum wave height under sea state 3.0 conditions nearly exceeds the workspace capabilities of the robotic arm system, and approaches half of the overall height of the Sea Fox vehicle. Since sea state 3.0 conditions will nearly exceed the workspace of the robot arms, it was decided this would be a good maximum sea state for validation of this capability and for demonstrating the arm recognizing the target may be outside of its reach.

In each test case, the sea state level was established to steady state in the tank before the refueling system was either manually tele-operated or deployed in autonomous mode. Initial validation of the system was performed under controlled, flat conditions with no added waves. Then, sea state 1.0 conditions were replicated with 6 inch waves induced at a 107 foot constantly repeating wave length. Finally, tests were performed at sea states 2.0, 2.5 and 3.0 with random wave heights and lengths.

Observers were stationed on the dock, in the ISO container, and on the boat to ensure the tests were run correctly and that there were no issues that needed immediate attention or a stop to the test. The observer in the boat also served to manually disconnect the puck system after each successful run and reset the system. The specifics of each test and all telemetry data were recorded in the command and control system for subsequent analysis. The key metric of each run was success or failure in docking and transferring fluid.

The refueling system proved durable and effective, even through light misting rain during setup and initial system testing. The compliant Octarm component functioned reliably, even under numerous and often violent collisions with the USV caused by random and un-sensed wave motion. The PA-10 system was able to maneuver quickly and precisely to follow the movements of the boat. The magnetic puck end effector was demonstrated to be reliable and rugged while making solid contact and detaching as needed as a safety feature against unexpected wave motion. The visual servoing techniques proved robust over a range of environmental conditions including rain, partial cloud cover, full sun, and wave spray.

TABLE II. presents a summary of the results of the tests over the range of sea states evaluated. Two different operators performed the tele-operation over a total of 65 trials during this investigation. Operator 2 demonstrated a 76% success rate while Operator 1 experienced a 54% success rate. This variability was not unexpected, but indicates the importance of the skill and training of the operator when under manual control. The autonomous mode overall gave a higher success rate (81%), though also operated at lower sea states. This illustrates the effectiveness of the visual servoing algorithms and the mechanical capabilities of the robotic arm system.

TABLE II. SUMMARY OF ATTEMPTED DOCKINGS FOR INITIAL TEST

Waves	Manual (Op 1)	Manual (Op 2)	Auto
Flat	3/6	-	3/3
6”, periodic	-	-	8/9
SS 2.0, random	5/8	10/10	19/25
SS 2.5, random	5/10	16/18	-
SS 3.0, random	-	5/13	-
TOTAL	**13/24 (54%)**	**31/41 (76%)**	**30/37 (81%)**

* (success/attempts)

The test result over all sea states combined shows that 74 of 102 trials were successful, allowing for a 73% success rate during the full integration test.

3) Final Refueling Demonstration

In the weeks following the full integration tests at the Aberdeen Test Center, the team formally demonstrated the system to the project sponsor, DARPA. In these demonstrations, the refueling system, the test configuration, and the test procedures were the same as in the earlier series of tests. The manual operators had additional training to further familiarize themselves with the system and the autonomous tracking algorithms were further tested and improved. The results of the manual and autonomous tests are summarized in TABLE III. .

TABLE III. SUMMARY OF ATTEMPTED DOCKINGS FOR FINAL DEMONSTRATION

Sea State	Manual (Op 2)	Autonomous
2.00	8/8	16/18
2.50	6/7	1/3
3.00	7/8	-
3.25	15/15	-
TOTAL	**36/38 (95%)**	**17/21 (81%)**

* (success/attempts)

For the tele-operation experiments, the operator who had greater success in the earlier test series was used exclusively. This operator ran approximately the same number of trials as in the first test series (38 compared to 41) and demonstrated a much higher success rate (95% compared to 76%). This higher total was achieved despite 15 of the demonstration trials being at sea state 3.25 (not attempted in the earlier tests), which moved the boat to the edge of the robot workspace. This large improvement in performance indicates the effectiveness achievable given a combination of operator aptitude along with training and experience with the system.

The overall success rate for autonomous mode was the same as in the initial trials (81%). While this verifies the consistency of the effectiveness of the automated system, the result, combined with the effectiveness now shown to be possible by manual operation, motivates further research and development in the sensing and visual servoing techniques implemented. Some improvements that will be investigated with further research in this area will include improving the response time and reaction speed of the rigid robotic arm to more quickly respond to changes in wave conditions, and updating the slow approach using the Octarm to initiate the docking sequence for refueling. Further operator training and increased speed of the system is expected to increase the success rate of the human operators for manually controlled docking.

The overall demonstration consisted of 59 total trials with 53 of them being successful, resulting in a 90% success rate over all sea states combined. This was considered to be highly successful for an initial feasibility study, demonstrating for the first time the ability for robots to track and contact, in a non-trivial way, a USV in realistic sea states. Ongoing work concentrates on refining the system and securing funding for a full-scale ship-to-USV fuel transfer demonstration at sea.

It is widely known that 2-dimensional fiducials, when used without stereo cameras, are less robust than when stereo cameras are used. The consideration of stereo cameras for this kind of work would improve the accuracy of the system. Additionally, a fielded system must survive in harsher environmental conditions, which is true for both the hardware and the visual servoing software. For example, the ARToolKit is sensitive to changes in lighting conditions (fog, sun angle, obstructions, glare, etc.) and the consideration of a solution that does not rely on the use of cameras may be necessary. Finally, the overall operational constraints on the use of this system in the field could also be re-investigated. If the refueling protocols differ from the restrictions imposed during these tests, then the system may be restricted for use under a lower sea state, which would improve the system success rate while further reducing risk to the systems experienced under higher sea states.

IV. Conclusions

The authors have described a new robotic approach for refueling unmanned surface vehicles (USVs) which could be used on the open water to refuel Navy vessels at significant sea states. The refueling system is made up of two robotic components: a conventional industrial robotic manipulator to pinpoint the location of the target fuel tank and a novel soft pneumatic arm to provide compliant and safe contact. A detachable magnetic end effector "puck" at the end of the refueling system ensures fuel transfer from the robotic system to the target fuel tank in the presence of unpredictable relative motions between refueling system and vessel. Both manual (joystick based) and autonomous (visual servoing based) operational modes were successfully implemented. The system was tested and demonstrated in an outdoor wave tank at the US Army Aberdeen Test Center, with the robotic refueling system on the dock and a US Navy Sea Fox vessel in the water. The robotic refueling system was demonstrated to transfer fuel to the target vessel under sea state 3.25 conditions (with wave variation greater than 1 meter).

This work is the first demonstrated use of a robotic system for fluid transfer to vessels in active sea states. The robot hardware system developed is novel in its combination of conventional (rigid-link) and continuum manipulators. The results show the utility of compliant continuum robot elements in accommodating impact during dynamic manipulation operations. Additionally, the ability of visual servoing techniques (without any predictive wave models) to successfully guide the mating process in active sea states is an important finding, offering the potential for future deployment of simple but robust systems.

Concurrent research to add a feedforward wave prediction model was initially considered in this research by not applied at the time of the final demonstration. This additional capability will be implemented as a future step to advance this research. Additionally, the use of more robust and specialized hardware would be required for a fielded system. However, the results presented in this paper demonstrate the feasibility of practical robotic solutions for autonomous shore-to-ship or ship-to-USV refueling.

Acknowledgment

This project was funded under the DARPA Rapid Autonomous Fuel Transfer Seedling Program and the U.S. National Science Foundation under award IIS-0904116.

References

[1] Anderson, V.C. and Horn, R.C. (1967). Tensor Arm Manipulator Design, Transactions of the ASME, vol. 67-DE-57, pp. 1–12.

[2] Bosse, A. B., Barnds, W. J., Brown, M. A., Creamer, N. G., Feerst, A., Henshaw, C. G., Hope, A. S., Kelm, B. E., Klein, P. A., Pipitone, F., Plourde, B. E., Whalen, B. P. (2004). "SUMO: spacecraft for the universal modification of orbits." Proceedings of the SPIE 2004 Conference. August 2004.

[3] Buckingham, R. (2002). Snake Arm Robots, Industrial Robot: An International Journal, vol. 29, no. 3, pp. 242-245.

[4] Csencsits, M., Jones, B.A., McMahan, W., and Walker, I.D. (2005), User Interfaces for Continuum Robot Arms, Proceedings IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, Canada, pp. 3011-3018.

[5] Galway, R. J. (2008). Autonomous Refueling of Unmanned Vehicles at Sea. In Proceedings of the ASNE Launch and Recovery Conference, May 2008.

[6] Guglielmino, E. Tsagarakis, N., and Caldwell, D.G. (2010). An Octopus-anatomy Inspired Robotics Arm, Proceedings IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, pp 3091-3096.

[7] Jones, B.A. and Walker (2006). I.D., Kinematics for Multisection Continuum Robots, IEEE Transactions on Robotics, vol. 22, no. 1, pp. 43–55.

[8] Lane, D.M., Davies, J.B.C., Robinson, G., O'Brien, D.J., Sneddon, J., Seaton, E., and Elfstrom, A. (1999). The AMADEUS Dextrous Subsea Hand: Design, Modeling, and Sensor Processing, IEEE Journal of Oceanic Engineering, vol. 24, no. 1, pp. 96-111.

[9] McMahan, W., Pritts, M., Chitrakaran, V., Dienno, D., Grissom, M., Jones, B.A., Csencsits, M., Rahn, C.D., Dawson, D., and Walker, I.D. (2006).Field Trials and Testing of "OCTARM" Continuum Robots, Proceedings IEEE International Conference on Robotics and Automation, Orlando, FL, pp. 2336-2341.

[10] Met Office (2010). "National Meteorological Library and Archive Face Sheet 6 – The Beaufort Scale." Version 01. National Meteorological Library and Archive, United Kingdom.

[11] Mitsubishi Heavy Industries, Ltd. (1991). Instruction Manual for Installation, Maintenance and Safety. Document 91-10023. Rev 1.

[12] Robinson, G. and Davies, J.B.C. (1999). Continuum Robots - A State of the Art, Proceedings IEEE International Conference on Robotics and Automation, Detroit, Michigan, pp. 2849-2854.

[13] Sherman, R. (1999). Underway Replenishment (UNREP). http://www.fas.org/man/dod-101/sys/ship/unrep.htm. Updated: 06 March 1999. Viewed: 02 November 2012.

[14] Tsukagoshi, H., Kitagawa, A., and Segawa, M. (2001). Active Hose: An Artificial Elephant's Nose with Maneuverability for Rescue Operation, Proceedings IEEE International Conference on Robotics and Automation, Seoul, Korea, pp. 2454-2459.

[15] Webster, R.J., and Jones, B.A. (2010). Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review, International Journal of Robotics Research, Vol. 29, No. 13, pp 1661-1683.