The NaviGator Autonomous Maritime System

ABSTRACT
Transferring data between the ocean surface and an operating Autonomous Underwater Vehicle (AUV) is a difficult and slow process. Current methods of un-tethered submersible communication have either a very limited data transfer rate or a prohibitively short range. In this paper, students of the University of Florida propose a new data transfer method that will supply the high data rates of a tethered system yet still maintain the advantages of a fully autonomous submersible. This paper reports the process of designing, testing, and proving this new approach. This method will improve communication between AUVs and the operator and enhance AUV operational efficiency and safety.

This approach uses an AUV paired with an autonomous surface vehicle (ASV) that carries a Remotely Operated Vehicle (ROV). During operation, the ROV is launched from the ASV. The ROV dives to the approximate operating depth of the AUV. Once the ROV is at depth, the AUV is acoustically summoned on an as-needed basis or based on a predefined schedule. When the transducer from the ROV begins transmitting, the AUV acquires the acoustic signal. Once in visual range, visual indicators on the ROV guide the AUV towards the docking mechanism on the ROV. When docked, the AUV transfers data to the ROV. That data is then sent to the ASV through the tether. The data on the ASV is stored onboard or transmitted to the user through wireless or satellite communications. Once the ASV data transfer is complete, the AUV is released from the ROV to continue its normal operation.

INTRODUCTION
Autonomous underwater vehicles (AUVs) are part of a growing industry and have proven to be useful in maritime operations. AUVs have been used to find underwater mines, inspect oil derricks, map parts of the ocean floor, and even searching for shipwrecks. Recently, AUVs have been used to search for missing aircraft such as the Malaysian Airlines Flight 370 (MH370). A Boeing 777, the same aircraft as MH370, is shown in Figure 1.

Figure 1. A Malaysia Airlines Boeing 777 [1].

During the search, an underwater signal was detected that may have originated from MH370’s flight recorder. Bluefin-21 drones, shown in Figure 2, were launched from a surface vessel to search for the submerged aircraft. Each AUV search operation lasted 24 hours. The submersible spent 16 hours at the operating depth, four hours diving and surfacing, and another four hours transferring the data to the operator once recovered [2].
Beacons used to locate the flight data recorders of downed aircraft are battery operated and must be located quickly after an accident. As MH370’s flight recorder battery waned, the need to receive data rapidly from the AUVs became critical. In addition to the difficulties of scanning the ocean floor for an aircraft or its wreckage, the overall cost of the search increased quickly after each day of searching. Within the first month, over 19 surface vessels from more than 20 different countries contributed to the search. Time Magazine estimated the first three months of the search cost more than $70 million. The loss of the aircraft and the ensuing search proved that AUV operations played a key role. However, with the costs of operating ships and AUVs during the search, it is evident that efforts to make the operations more efficient and affordable are warranted.

EXISTING TOOLS AND METHODS

Communicating with submersibles is difficult and complicates underwater operations. Tools AUV operators can use to monitor the vehicles include acoustic modems as shown in Figure 3, light fidelity (Li-Fi), and radio transmissions.

Acoustic modems, the most popular tool, are omni-directional, support extensive range, and are not susceptible to environmental conditions such as water clarity. However, most production-grade acoustic modems are only able to achieve data rates up to 50 Kbps [7]. Due to the attenuation experienced by sound waves traveling through the water, modems with higher data rates have transmission ranges that are too short to be useful for AUVs.

Another form of underwater communication is Li-Fi. Li-Fi uses light to transfer data. It can provide exceptional underwater data transfer rates [7] [8] [9]. However, the transmission range is limited because the light must be observed. Particulates in the water or external light sources, such as sunlight, can interfere with communications.

Finally, radio transmission can also support underwater wireless communications. While most radio frequencies are completely absorbed within a meter of water, some very low frequencies can penetrate deep enough for submarines to receive them. Extremely low frequencies have been used to communicate with submarines but have very low bandwidth [10]. Therefore, radio transmissions are not effective in transferring large amounts of data between the AUV operators on the ocean’s surface and the submersible located thousands of meters below. With the limitations of underwater communications, real time monitoring of the submarine’s high-bandwidth sensors is not possible because little information can be transferred.
During AUV operations, human operators must be on location and actively involved. In addition to supervising the launch and recovery processes, operators must also observe the submarine’s underwater status. Operators on the surface typically monitor the data via acoustic modems. For most AUV operations, the imaging SONAR is the most useful sensor. The active SONAR provides visual data of the ocean floor such as the image shown in Figure 4. However, the active SONAR data rate can be as high as 10 Mbps [11]. At the modem’s maximum 50 Kbps data rate, more than three minutes would elapse before receiving one second of data from the imaging SONAR. Acoustic modems are too slow to keep up with the demands of real-time SONAR data transfer.

Cameras are another useful underwater sensor. However, cameras can require an even higher data transfer rate than SONAR, depending on the camera’s specifications. To support the immense amount of data recorded by the submarine, most AUVs require the submersible to be recovered first. Operators must then download the recorded data directly from the submarine. Depending on the time spent underwater, the data could be more than 16 hours old. When timing is critical, as in the search for MH370, 16 hours of data delay is unacceptable.

This paper proposes a new system to improve AUV communication with surface users. Ideally, the new system will also reduce the need for frequent human interventions.

REMOTELY OPERATED VEHICLES AND AUTONOMOUS SURFACE VEHICLES IN AUV OPERATIONS

One way to solve the communication issue between the surface and the submersible, is to use a tether. ROVs, like the one shown in Figure 5, are submarines that have attached tethers that are thousands of meters long.

![Image of ROV](image)

Figure 5. NOAA’s Global Explorer [13], a remotely operated vehicle. Note the large yellow tether connecting the submersible to the operator.

The tether supports high data transfer rates and sometimes provides power to the vehicle. Because of the physical connection, tethers allow high data rate sensors, such as camera images and SONAR data, to be streamed in real time. The tether presents several challenges, however:

- ROVs require a human operator to continuously supervise the vessel, whereas AUVs do not.
- ROVs require a much larger support surface vessel, when compared to AUV operations, to carry the large reel holding the thousands of meters of tether cable.
- To support the weight and drag of the tether, deeper ROV operations require
larger ROVs with larger thrusters to overcome the resistance.

- Operating longer tethers with bigger ROVs requires more manpower to move the larger equipment.
- Conducting longer ROV operations with more personnel increases the overall cost.
- Longer AUV missions also suffer from the costs associated with retaining operators at sea.

A principal engineer in the Department of Applied Ocean Physics and Engineering from Woods Hole Oceanographic Institution, a private maritime research facility, estimated their cost of AUV operations: "Cost depends on the AUV. Small R100 is cheap $500 to $1000 per day. Deep R6000 with Launch and Recovery and all support equipment $10,000/day." [14].

Efforts to develop platforms that would reduce or eliminate the need for excessive manpower have led to the development of Autonomous Surface Vehicles (ASV). Figure 6 shows an example of an ASV.

With this navigation system, ASVs are able to travel across large bodies of water without human intervention and still arrive within meters of the desired destination. Submersibles are unable to use GPS while underwater and must depend on internal sensors. Because of noise, the solutions provided by the internal sensors drift over time and will experience a decrease in accuracy.

Although ASVs are effective autonomous research platforms, by themselves, they are not very useful in underwater operations. Light does not travel far through water preventing cameras on the boat from seeing objects at the bottom of the ocean. Due to attenuation, imaging SONAR is limited to a range of several hundred meters. To be useful, an ASV with an imaging SONAR would be limited to shallow water; deep-sea searches would not be possible.

All three platforms—ASVs, AUVs, and ROVs—have strengths and weaknesses when performing underwater operations. A system designed to use the strengths of all three platforms would greatly improve AUV operations. An autonomous system would decrease the cost of operating the system to a fraction of the current operations cost by reducing the required manpower. This paper presents one such solution.

**THEORY OF THE SYSTEM**

One way of combining the three systems would require placing the ROV onboard the ASV. Such a system would work like this:

1. The ASV travels to the location of the operating AUV.
2. Once on station, the ASV launches the ROV, and the ROV dives to a predetermined depth. The depth could be as deep as the AUV or limited by the length of the tether.
3. Eventually the AUV connects with the ROV and transfers its data.
4. Once data transfer is complete, the AUV disconnects from the ROV and continues operating without resurfacing.
5. The data from the AUV is sent to the ASV via the tether.
6. The data is transferred to the operator from the ASV.
7. The ROV is recovered when operations conclude.

Harnessing the strengths of each platform would create an effective underwater operations system.

The benefits from using this system are many. One benefit is the ability to download data from the AUV without requiring surfacing and recovery. Some AUVs have a diving speed of 45 meters/min and an ascent speed of 135 meters/min [16]. At this rate, it would take the AUV almost two hours to reach the estimated depth of MH370 at 4,500 meters [17] and more than 30 minutes to surface. Adding another two hours for AUV preparations, launching, and recovery brings the entire process close to four hours. During the four hours, the AUV would not be able to perform its missions, and the time would be lost. Because of this loss in efficiency, operators desire to maximize the underwater time between AUV launch and recovery to make the most of the operation. However, with the three-platform system, data from the AUV could be transferred to the user without requiring the AUV to surface. This allows AUV missions to be divided into smaller runs where the operator receives smaller amounts of data more often. The search missions would also be more effective because the operators can react and redirect the search in response to the more real-time data.

The three-platform system also solves the cumbersome problem of submersible vehicle recovery. Surfacing AUVs can be difficult to locate especially in rough seas [18]. When surfaced, most AUVs are barely above the water and can only be seen when operators are within several miles. If the AUV surfaces in the wrong location, such as underneath a ship or iceberg, the vessel could be damaged or even lost. Using the ROV to connect to the AUV, the AUV could be reeled out of the water, which would simplify recovery and safeguard the submersible. Docking underwater is advantageous because the ocean is much calmer beneath the surface. Engineers have designed a system that uses an ASV-dragged, drogue-based mechanism to recover the AUV [19]. A drogue-based recovery system also benefits from the calm conditions of underwater docking. However, because the ASV must pull the drogue to maintain depth, the method is not effective in areas that may restrict vessel maneuverability, such as narrow channels or deep crevices.

In addition to wireless communications, the ASV also provides controllable mobility. Engineers designed a similar idea in using ROVs with AUVs that involved a buoy launched from an aircraft that used a tethered ROV [20]. The ROV from the buoy would dive to the desired depth and attach with another submersible. However, the buoy system was subject to any ocean currents or winds. The buoy was unable to maintain position and would pull the ROV away from the operating area.

Using a different approach, much research has explored the development of anchored buoys that provide docking mechanisms, data transfer, and even charging [21] [22] [23] [24]. However, these buoys are fixed and would be very difficult to implement in deep waters. If the AUV operations began to move away from the anchored buoy, the increased time required to travel between the AUV and buoy would eventually negate the benefits of underwater recovery. The anchored system had a limited operating depth. In very deep water, the cable length required to keep the buoy anchored would be prohibitive.

In contrast, an ASV, using its thrusters, could maintain its position or follow the operations of the AUVs. The ASV system would not be depth-dependent and could overcome mild ocean currents and winds. To prove the above concepts, students at the University of Florida Machine Intelligence Laboratory (MIL) are developing a prototype called the NaviGator Autonomous Maritime System (AMS).

**PROOF OF CONCEPT**
The objective of the NaviGator AMS is to validate the above proof of concept in a real
environment. MIL students are developing three vessels:

- **NaviGator** the ASV
- **Anglerfish** the ROV
- **SubjuGator** the AUV

All three platforms will operate in freshwater and ocean environments. The proof of concept will be considered successful when data from SubjuGator is transferred to NaviGator through Anglerfish.

**NAVIGATOR ASV**

NaviGator ASV, shown in Figure 7, is a Wave Adaptive Modular Vessel (WAMV) outfitted with a computer, sensors, and thrusters. The WAMV consists of two inflatable pontoons connected by a suspension system and a large platform for the mounting of sensors, computers, and other equipment. The suspension system dampens the vessel’s oscillations, caused by high sea states, and prevents the rear-mounted thrusters from leaving the water making propulsion more efficient by allowing the hull to conform to the waves [25] [26]. The suspension system also attempts to keep the platform marginally horizontal. Table 1 provides an overview of the vessel.

![Figure 7. The NaviGator ASV operating at Lake Wauburg. NaviGator ASV uses four trolling motors to propel it through the water.](image)

<table>
<thead>
<tr>
<th>Thruster force</th>
<th>Four thrusters, 36 kg each</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>Two 24 V lithium ion batteries</td>
</tr>
<tr>
<td>Operating time</td>
<td>5 hours</td>
</tr>
<tr>
<td>Hull material</td>
<td>Aluminum structure on inflatable pontoons</td>
</tr>
</tbody>
</table>

**Table 1. Specifications of NaviGator, the ASV.**

For propulsion, NaviGator uses four trolling motors that each produces 36 kg of thrust. The motors are mounted in an orientation that allows movement in all three degrees of freedom available to surface vessels (sway, surge, and yaw). Two 24 V lithium ion batteries, with 104 Ah of current, provide approximately five hours of operation. NaviGator has a maximum range of 15 nautical miles.

A custom built Intel I7 based computer with the Ubuntu Linux operating system and custom software utilizes the onboard sensors and controls the thrusters. A student-designed Integrated Navigation System (INS) estimates NaviGator ASV’s roll, pitch, and yaw. The INS utilizes accelerometers, gyros, magnetometers and GPS to estimate position. Cameras and a LIDAR provide the system with data that can be used to avoid obstacles. A large radio antenna provides wireless communications between the boat and the operator. NaviGator ASV can carry and launch the ROV from beneath the main platform.

**ANGLERFISH ROV**

Anglerfish [27], shown in Figure 8, is designed to be controlled by the NaviGator ASV. A tether is connected between the ROV and the ASV that provides power to the ROV and communication between the two. The 30 m tether is strong enough to be used as a method to recover the submersible. Table 2 gives the specifications of Anglerfish.

<table>
<thead>
<tr>
<th>Weight</th>
<th>295 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>5.5 m</td>
</tr>
<tr>
<td>Top Speed</td>
<td>3 kt</td>
</tr>
<tr>
<td>Propulsion type</td>
<td>Brushed trolling motors</td>
</tr>
</tbody>
</table>

**Table 2. Specifications of Anglerfish.**
Figure 8. The Anglerfish ROV. The metallic discs below the clear dome are the electromagnets used to attach to the SubjuGator AUV steel mounting point.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>7 kg</td>
</tr>
<tr>
<td>Top Speed</td>
<td>1 kt</td>
</tr>
<tr>
<td>Propulsion type</td>
<td>Brushless motor thrusters</td>
</tr>
<tr>
<td>Thruster force</td>
<td>Six thrusters, 2 kg each</td>
</tr>
<tr>
<td>Power supply</td>
<td>Powered through tether</td>
</tr>
<tr>
<td>Operating time</td>
<td>5 hours</td>
</tr>
<tr>
<td>Max depth</td>
<td>100 m</td>
</tr>
<tr>
<td>Hull material</td>
<td>Acrylic tube with 3D printed structure</td>
</tr>
</tbody>
</table>

Table 2. Specifications of the Anglerfish ROV.

An acrylic water tight tube contains the electronics. A 3D printed structure is designed around the tube to accommodate the mounting of the thrusters, lights, and actuators. Six thrusters are mounted in a configuration that allows movement in all six degrees: roll, pitch, yaw, heave (depth), surge, and sway.

A Raspberry Pi 3 development board running Ubuntu Linux manages the thrusters and monitors the sensors. Anglerfish’s Inertial Measurement Unit (IMU) estimates the submersible’s roll, pitch, and yaw. The development board also monitors a pressure sensor that determines the submarine’s depth. Visual feedback to the Anglerfish ROV is provided through a camera mounted inside the dome. A small, wireless router is installed inside the water tight tube and placed at the front of the ROV. This router is used to establish a short range wireless network link with the SubjuGator AUV.

Students considered several ideas for the docking process between Anglerfish and SubjuGator. A popular AUV docking method requires specific body geometry for docking. This method utilizes a cone-like cage that a torpedo-shaped AUV can physically enter [28] [29]. An example of the cage docking system is shown in Figure 9. This mechanism limits the types of AUVs that can be docked. To accommodate SubjuGator AUV’s box-like frame, students designed an alternative docking mechanism.

Figure 9. A cage-type docking system for AUVs [28]. This system is dependent on the body geometry of the AUV.

Docking with SubjuGator is achieved with the capturing system mounted underneath the dome of Anglerfish. The system consists of two electromagnets and four LEDs shown in Figure 10. The LEDs provide a visual reference for SubjuGator during the docking process. The LED orientation is inspired by research into space docking techniques for underwater docking [30]. The space docking mechanism is shown in Figure 11. During wireless data transfer, the electromagnets hold the two submersibles together. Once the data transfer is complete, the vehicles will disengage.
Figure 10. The docking mechanism on Anglerfish. Four blue LEDs are used by SubjuGator as a visual reference during the docking procedure.

Figure 11. A flight experiment target used for space navigation [30]. This was the inspiration behind the light pattern of Anglerfish’s blue LEDs.

**SUBJUGATOR AUV**

Students selected SubjuGator as the prototype AUV because of its modularity, maneuverability, and underwater operating time. Figure 12 shows the front of the vessel. Modularity is achieved by the carbon fiber frame that permits the easy mounting of additional components. One such device is the steel docking point for Anglerfish. Table 3 gives the specifications of SubjuGator.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
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</tr>
<tr>
<td>Top Speed</td>
<td>1 kt</td>
</tr>
<tr>
<td>Propulsion type</td>
<td>Brushless motor thrusters</td>
</tr>
<tr>
<td>Thruster force</td>
<td>Eight thrusters, 9 kg each</td>
</tr>
<tr>
<td>Power supply</td>
<td>Two 24 V lithium polymer batteries</td>
</tr>
<tr>
<td>Operating time</td>
<td>1.5 hours</td>
</tr>
<tr>
<td>Max depth</td>
<td>150 m</td>
</tr>
<tr>
<td>Hull material</td>
<td>Aluminum hull with carbon fiber structure</td>
</tr>
</tbody>
</table>

Table 3. Specifications of the SubjuGator AUV.

SubjuGator consists of two waterproof aluminum hulls mounted on an aluminum plate and held together with a carbon fiber frame. The primary hull contains the computer and power management circuitry. The navigational equipment is located inside the secondary hull. Eight thrusters are mounted in an orientation that allows the AUV to move in all six degrees of freedom. Two 24 V batteries, connected in series, support system operation for 90 minutes.

Using the Ubuntu Linux operating system and custom software, the server grade, Intel Xenon processor based computer in the submarine’s primary hull controls the vessel. An IMU provides the roll, pitch, and yaw of SubjuGator. The Doppler Velocity Log (DVL) sensor, shown in Figure 13, is mounted to the bottom of the submarine. The sensor provides an estimate of
the vehicle’s velocity. Depth is determined by a pressure sensor. Four hydrophones are used as part of the passive SONAR. Finally, the two cameras in the front of the submarine provide stereo vision feedback that is used during the docking procedure.

![Figure 13](image1.png)

Figure 13. This image shows the bottom of the DVL mounted on SubjGator. The red discs use ultrasonic signals to determine SubjuGator’s velocity in the water.

Mounted on the front, horizontal beam of SubjGator is the docking point shown in Figure 14. The device consists of a 3D printed mount and a steel plate. The steel plate is used as the holding point for the ROV’s electromagnets. A Wi-Fi adapter is installed inside the 3D printed mount. The adapter is used to wirelessly connect to the router on Anglerfish.

![Figure 14](image2.png)

Figure 14. A close up of the mounting point on SubjGator. The wireless adapter is located behind the steel plate.

**SPECIALIZED HARDWARE AND SOFTWARE**

All three systems utilize Ubuntu Linux and the Robot Operating System (ROS). ROS is a software framework that is specific to and greatly enhances the coding of robotic software [31]. ROS allows data, in the form of messages, to be shared across a network among different programs and platforms. Any program can publish or receive messages. This ability forms a cloud-like network that allows for decentralized operations among multiple systems. High volumes of data can be sent from a less powerful computer to a more powerful computer where it can be analyzed more rapidly, a function that is critical in controlling Anglerfish ROV by using NaviGator ASV’s more powerful computer.

Wi-Fi was selected as the communication medium because it works at short ranges underwater and does not require physical contact. 2.4 GHz Wi-Fi has been proven to work reliably at ranges under 13 cm [32] [33]. Figure 15 shows the results from a study of transmission distances of 2.4 GHz underwater wireless communications. Because of underwater wireless range, Wi-Fi communications require less positional accuracy than physical connections. When Anglerfish can connect to SubjGator’s mounting block, wireless communications can be established. The estimated distance between the router on Anglerfish and the adapter on SubjGator, when the two are docked, is approximately 10 cm.

![Figure 15](image3.png)

Figure 15. A graph showing packet loss versus distance between antennas of underwater 2.4 GHz transmissions [32]. Once Anglerfish is docked with SubjGator, the distance between the wireless antennas is approximately 10 cm.

Anglerfish’s sensor suite provides roll, pitch, yaw, and depth (heave), but the sensors cannot
provide surge and sway. Estimates of all six degrees are necessary to accurately control the ROV. On more sophisticated submersibles, surge and sway can be measured by taking the double integral of the accelerometer readings. Unfortunately, Anglerfish uses affordable, yet somewhat noisy accelerometers, which prohibits the use of taking the double integral of the accelerometer data for surge and sway calculations. Another sensor that could be used to measure surge and sway is a DVL such as the one mounted on SubjuGator AUV.

DVLs are very expensive (SubjuGator’s DVL was $25K), and mounting the sensor would require drastic changes to the mechanical structure of Anglerfish. Therefore, another solution was implemented. Inspired by indoor quadcopter controls using external cameras [34], students developed a method to measure the ROV’s velocity using an external sensor. In clear water, a submerged, downward-looking camera mounted on NaviGator ASV’s hull can be used to track Anglerfish’s relative movements. Figure 16 shows NaviGator ASV’s downward-looking camera. Adding a bright green LED to the submersible improves the camera’s ability to track the ROV’s movements. Figure 17 shows the LED on Anglerfish.

Green was selected because of its low absorption in water [35]. The observed movements from NaviGator ASV’s camera are combined with the sensor data provided by Anglerfish’s onboard sensors to create an accurate estimate of the ROV position. However, because the visual tracking depends on water clarity, this solution may not be reliable and will be used until an acoustic-based tracking system (presently under development in MIL) is available.

Figure 16. NaviGator ASV’s submerged, downward-looking camera. The camera is mounted inside a waterproof case.

The acoustic-based system consists of an active transducer and a passive SONAR system on NaviGator ASV. Anglerfish is outfitted with an acoustic transducer that periodically emits an acoustic signal (ping). NaviGator ASV uses a student-designed passive SONAR system, shown in Figure 18, that monitors signals from four hydrophones to determine the bearing of the acoustic transmissions [36].

Figure 17. The white dome is the LED bank. It will emit a green light that NaviGator ASV’s submerged camera will track. Based on the movements of the green LED, NaviGator ASV can determine Anglerfish’s relative position and velocity (in two dimensions) in the water.

The four black hydrophones and the 3D printed mount are in the foreground. The student-designed SONAR circuit board is in the background.
The bearing estimated from the SONAR on NaviGator ASV is combined with Anglerfish’s reported depth. This combination provides an accurate three-dimensional position of the ROV, relative to the ASV. The acoustic system can operate within an estimated 45 meter maximum distance between the two vessels. When compared to the camera-based method, the sound-based system provides a longer range and does not depend on water clarity.

Both NaviGator ASV and SubjuGator are outfitted with the same type of passive SONAR, and both listen to the ROV’s transmissions. However, instead of passively tracking the ROV, SubjuGator uses its SONAR to approach the ROV during the docking process. SubjuGator estimates the ROV’s bearing and depth using a two-dimensional fix (angle and declination).

DOCKING AND DATA TRANSFER
The following steps outline the three-vessel operation from deployment to docking to data transfer:

1. NaviGator ASV is deployed and maneuvers to a given point.
2. Once on station, the ASV holds its position and heading.
3. Anglerfish is then launched from the ASV, begins transmitting once wet, and descends to a desired depth.
4. When the ROV reaches the desired depth, it maintains its position and heading.
5. SubjuGator is then deployed within SONAR detection range of the ROV.
6. The AUV descends to roughly the same depth as Anglerfish and begins listening for the acoustic transmissions.

Next the homing and docking process begins when the AUV determines the first good bearing estimate:

1. Using the good bearing estimate, the AUV begins maneuvering towards the direction of the transmissions.

2. SubjuGator updates Anglerfish’s perceived bearing with each new received transmission and continues moving towards the emitter.
3. During this process, SubjuGator constantly searches for the reference LEDs on Anglerfish to begin proper docking alignment.
4. Once SubjuGator recognizes the LEDs on Anglerfish, the AUV shifts to a visual docking mode.
5. The AUV maneuvers into Anglerfish using the lights as a visual reference as shown in Figure 19.
6. When the AUV is near the ROV, the electromagnets on Anglerfish pull and hold both vessels together, completing the homing operation.

Figure 19. Before transferring data, Anglerfish connects to the steel mounting point on SubjuGator using two electromagnets.

The final process is the data transfer:

1. After the ROV connects to the mounting point, SubjuGator attempts to connect to the wireless router on Anglerfish.
2. Establishing a wireless connection allows SubjuGator to transfer files to Anglerfish.
3. The files are then relayed to the ASV.
4. Once the transfer is complete, SubjuGator disconnects concluding the exchange.

Operators on shore maintain contact with all three platforms. However, the ASV and ROV are on a separate network from the AUV. Data
from SubjuGator is transferred to NaviGator ASV’s network. Once data from SubjuGator is transferred to NaviGator ASV’s network, the above process, currently a proof of concept, will be considered proven.

FUTURE WORK
Deploying more than one AUV for use with the ASV/ROV system would further improve the efficiency of AUV operations and would not require additional man power. Multiple AUVs could divide the work and efficiently cover a larger search area as a combined system. Each AUV could then be summoned individually using an assigned acoustic signal. As the flotilla of submersibles advanced with their search areas, the ASV and ROV could follow along reducing the distance each AUV would need to travel during the homing period. This system would greatly improve operational efficiency during operations such as mapping or searching the ocean floor.

Placing an AUV recharging system on the ASV would allow the vessel to charge an AUV through the ROV. Assuming the ASV could recharge itself with a renewable energy source such as solar energy, and this could be shared with AUVs, the AUVs could stay submerged and operate indefinitely. Non-contact recharging methods would allow more flexibility in the recharging process and could accommodate a variety of AUV hull shapes.[37][38].

CONCLUSION
This paper presents a three-vessel system for underwater operations. Combining the strengths of the tethered ROV with the utility of the AUV improves underwater operations by creating a high-speed underwater communications path. Docking the AUV with the ROV also eliminates the need for the AUV to surface in order to transfer sensor data to the operators. When the above method is implemented through the use of an unmanned ASV, the high costs associated with long AUV operations can be greatly reduced by eliminating the need for personnel at sea.

REFERENCES


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