The Evolution of an Autonomous Unmanned Surface Vessel and Software for Hydrographic Survey

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Abstract

In 2017, Leidos participated in both the Gulf of Mexico Unmanned Systems Operational Demonstration (GoMOD) and the Advanced Naval Technology Exercise 2017 (ANTX 2017). Leidos used the *R/V Pathfinder* vessel, which is the test platform for the *Sea Hunter* medium displacement unmanned surface vessel (MDUSV), and performed Multibeam Echosounder (MBES) hydrographic surveys in autonomous mode. The vessel autonomously maintained COLREGs (Convention on the International Regulations for Preventing Collisions at Sea) compliance reacting to both real-world and simulated "interferers" to demonstrate the ability of the system to divert from the planned survey line during a COLREGs maneuver and then re-acquire the survey line once safe to do so, while the survey acquisition software autonomously controlled and logged hydrographic data to International Hydrographic Organization (IHO) Order 1a standards. This paper presents the *R/V Pathfinder* systems, testing, and autonomous survey results.

Introduction

In 2012, Leidos, Inc. began developing an autonomous surface vessel (ASV) for the Defense Advanced Research Projects Agency (DARPA) Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) program. The ASV development included autonomous situational awareness and adherence to COLREGs, as well as autonomous monitoring of onboard conditions and resources to make adjustments to maintain efficiency and meet specified mission duration requirements. The vessel was launched in January 2016 and christened *Sea Hunter* in April 2016. The *Sea Hunter* is a trimaran wave piercing hull design with speeds in excess of 20kts. The 132-foot vessel was designed for trans-oceanic crossings with mission duration of over 70 days. While the *Sea Hunter* was designed for autonomously trailing submarines, its autonomy capabilities are expandable to support a wide range of missions.

To support the DARPA ACTUV program, Leidos acquired the vessel *R/V Pathfinder* (**Figure 1**), as a test platform for *Sea Hunter*. *R/V Pathfinder* is an aluminum catamaran research vessel, 40-feet in length with a 14-foot beam. The *R/V Pathfinder* was outfitted with architecturally consistent control systems as used on the *Sea Hunter*, allowing the *Pathfinder* to perform test scenarios prior to the autonomy software being deployed, or updated, on *Sea Hunter*. The vessel's autonomous system runs on an Advanced Telecommunications Computing Architecture (ATCA) chassis using open source code and a modified version of Leidos' Integrated Survey System 2000 (ISS-2000) software, interfaced to the navigation and situational awareness sensors (such as radars, sonars, automated identification system [AIS], optical sensors, and meteorological sensors), as well as the engine controls during unmanned, autonomous operations.

For the 2017 GoMOD and ANTX demonstrations, Leidos leveraged its existing advanced autonomy capability on the *R/V Pathfinder* to expand capabilities to include a hydrographic survey component. The GoMOD event took place from 30 May through 01 June 2017, and demonstrated an unmanned systems role in Fleet and Joint Operations. The event goals included the evaluation of emerging unmanned technologies and hydrographic collection in support of undersea warfare. ANTX is an annual event which showcases Naval Warfare Centers, academia, and industry emerging technologies that have naval applications. The 2017 event took place in August 2017 simultaneously at the Naval Undersea Warfare Center (NUWC) in Newport, Rhode Island and at the Naval Surface Warfare Center (NSWC) in Panama City, Florida.

Figure 1. *R/V Pathfinder*

Autonomous Survey Requirements

Prior to the 2017 demonstrations, Leidos identified key vessel control system and survey data acquisition system requirements to successfully complete an autonomous hydrographic survey including the following:

1. The vessel control system must be capable of:
    a. Maintaining course over predefined survey lines within ± 5 meters
    b. Maintaining situational awareness such that it can remain COLREGs compliant
    c. Resuming a survey line after executing a COLREGs engagement or avoidance maneuver
2. The survey data acquisition control system must be capable of:
    a. Confirming system readiness to commence survey operations
    b. Automatically handling all aspects of sound speed profile (SSP) data
    c. Continuously monitoring major and subsystem health, and reporting when non-compliant
    d. Logging key survey events and producing standardized time stamped reports
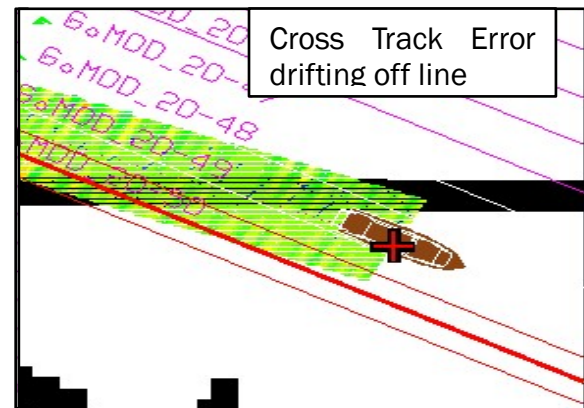
Preliminary Field Testing

In preparation for the ANTX 2017 demonstration, Leidos conducted the first on-water tests of the autonomous vessel controls for a hydrographic survey on the *R/V Pathfinder* on 13-14 May 2017. This first test was needed to determine how the existing autonomy software would perform the line-following behavior needed for hydrographic survey, given that the original ACTUV mission did not include line-following behavior, but rather waypoint seeking behavior. The *R/V Pathfinder* was outfitted with a standard suite of survey equipment and a vessel control system as outlined in **Table 1**. To facilitate faster transits between the dock and the test survey area, the multibeam transducer was not installed for this first test. However, the multibeam topside unit was configured to output simulated data which allowed complete system functionality to be tested.

Table 1. Primary Systems onboard the *R/V Pathfinder*

Primary System	Description of Use
Leidos Integrated Survey System 2000 (ISS-2000)	Integrates survey subsystems, logs all survey data, controls timing for all data, and Survey Planning
Leidos iNavLog	Automatically captures key survey events and outputs survey logs in Microsoft Excel format.
Leidos Autonomous Path Planner (ISS-2000A)	Controls vessel systems
Teledyne RESON SeaBat 7125 Multibeam Sonar	Collects multibeam bathymetry
AML Moving Vessel Profiler (MVP30)	Collects sound speed profile data
Applanix Position and Orientation System, Marine Vessel (POS/MV) v5	Provides position, heading, and motion corrections

Various autonomy settings were tested using traditional long lines with only a beginning and ending waypoint. The system achieved a cross track error at the start of line between 3-9 meters; however the vessel deviated from the line by as much as 65 meters along the length of the line (**Figure 2**). The distance of cross track deviation from the line was based on the amount of set and drift the vessel experienced between waypoints.

As a quick fix performed in the field, survey lines were generated that incorporated intermediate waypoints which greatly improved the achieved cross track error along the length of the survey

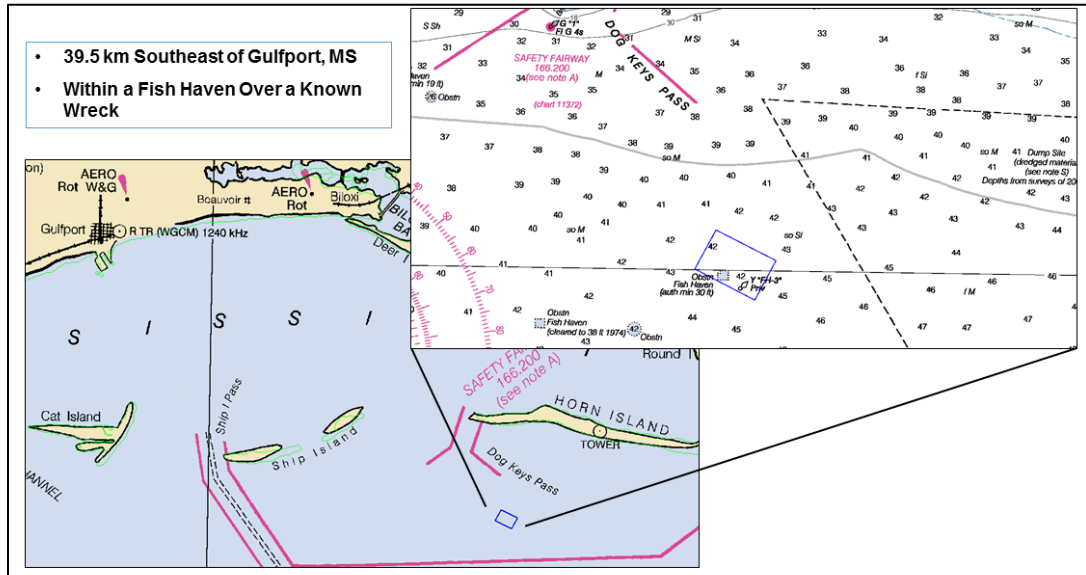**Figure 2.** *R/V Pathfinder* **Line Keeping Prior to Upgrades**

line, varying proportionately with the amount of cross current and wind. With no cross current and wind the vessel followed the survey line with little-to-no cross track error. As cross current and winds increased the vessel would maintain a straight line, a given distance off the survey line. In order to consistently achieve the line-following tolerances of ±5 meters established in the requirements, it was determined a true line-following behavior would need to be added to the autonomous vessel control system.

Adding the intermediate waypoints also greatly improved the behavior for returning to the survey line after deviating course for a COLREGs maneuver. The gap created as a result of a course deviation was limited to the distance between the intermediate waypoints as the vessel would return to the next active waypoint. The intermediate waypoint approach did however illuminate an issue of the vessel control system and autonomous path planners. When a waypoint was collocated with an area identified as a keep out area, such as a charted object or static vessel traffic, the autonomous path planner would fail to initiate the mission as it determined the mission could not be obtained.
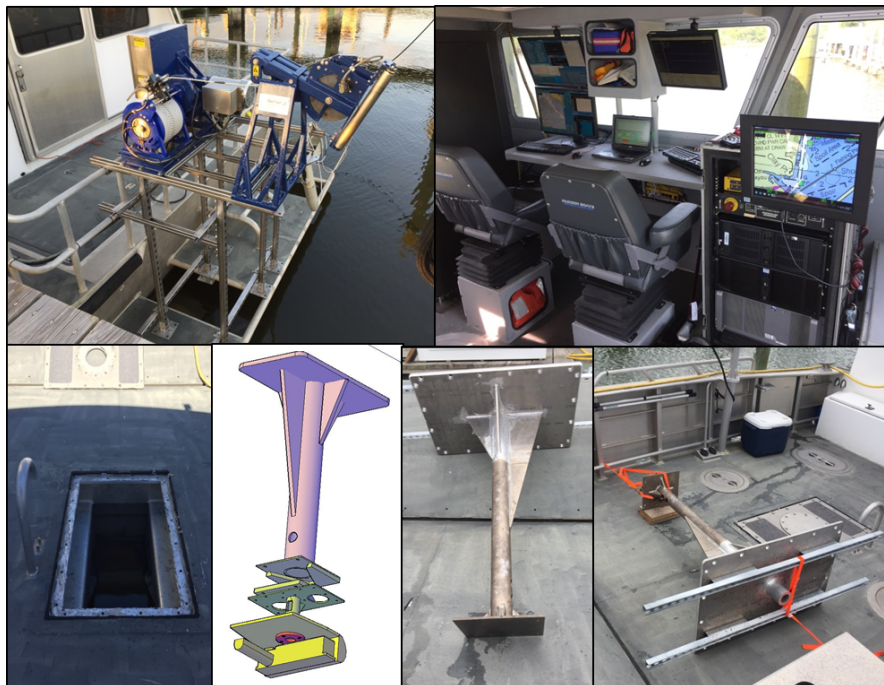
GoMOD Survey

Leidos conducted its first autonomous hydrographic survey effort in support of GoMOD on 25-26 May 2017 onboard *R/V Pathfinder*. Results from the GoMOD survey were used to further both the autonomous vessel control system, and data acquisition control system, for use at ANTX 2017. The GoMOD survey was conducted within a fish haven, over the charted wreck, *Liberty*, approximately 39.5 kilometers (km) southeast of Gulfport, Mississippi (**Figure 3**).

Figure 3. GoMOD Survey Area (BLUE Rectangle) 39.5km Southeast of Gulfport, MS

GoMOD Operational Scenario

The *R/V Pathfinder* was outfitted with a standard suite of survey equipment and vessel control systems as outlined in Table 1. The RESON 7125 transducer was pole mounted in the bow's moon pool, and the AML MVP30 was mounted on the aft swim platform (**Figure 4**).

Figure 4. GoMOD Survey Equipment Suite

The *R/V Pathfinder* piloted from the dock and was stopped 10-15 minutes from the survey area and the MVP30 SSP towfish was manually deployed. Once the SSP towfish was in the water the mission plan was engaged, allowing for autonomous vessel control and survey data acquisition. The SSP was set to auto deploy at set intervals, and each cast was automatically sent to ISS-2000. The ISS-2000 software automatically filtered the SSP cast using a moving average filter and then automatically applied the cast to the bathymetric data.

The ISS-2000 software captured the raw datagram from the RESON 7125, generated a Generic Sensor Format (GSF) data file, and applied all correctors for motion, SSP, position, heave, etc. in real-time (**Figure 5**). Upon reaching the ending waypoint for each survey line, the ISS-2000 software was programmed to automatically change all data filenames and backup the previous line's data to a remote storage device. The various settings for the RESON 7125 were predefined for the survey area water depths and bottom characteristics, however there was no feedback control by ISS-2000 to automatically change operational settings such as power, gain, range scale, gates, or absorption.

Leidos' iNavLog program interfaces with ISS-2000 and reads the messages that are generated during key events such as the start and end of survey lines, generation of a new SSP, application of SSP, and when the vessel exceeds predefined criteria (such as cross track error, or exceeding maximum speed limits). The key event messages are captured in a database which can generate standardized time-stamped reports in Microsoft Excel format.

As the line-following autonomous vessel control behavior was still under development, the GoMOD survey utilized the intermediate waypoints method as determined during the on-water testing earlier in the month. In order to ensure survey data consistency and quality, the path planners were set to maintain a target speed of 7.5kts with a maximum allowed speed of 8.0kts, which ensured online speeds would not exceed an 8kt limitation during COLREGs maneuvers, or when transiting to the next waypoint.
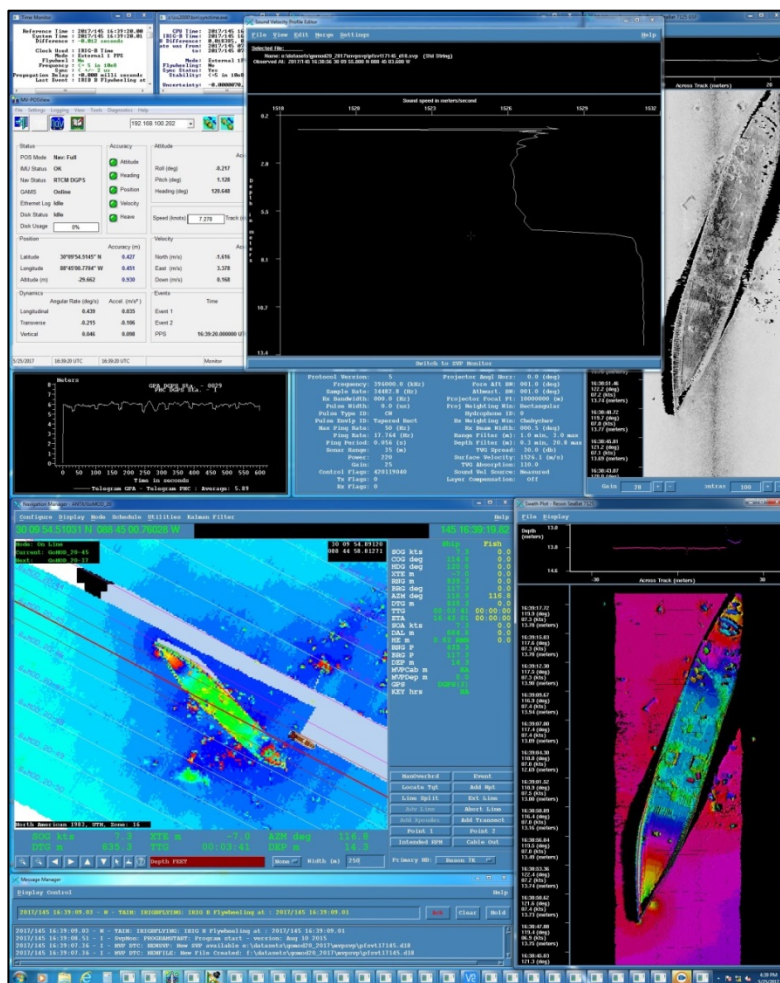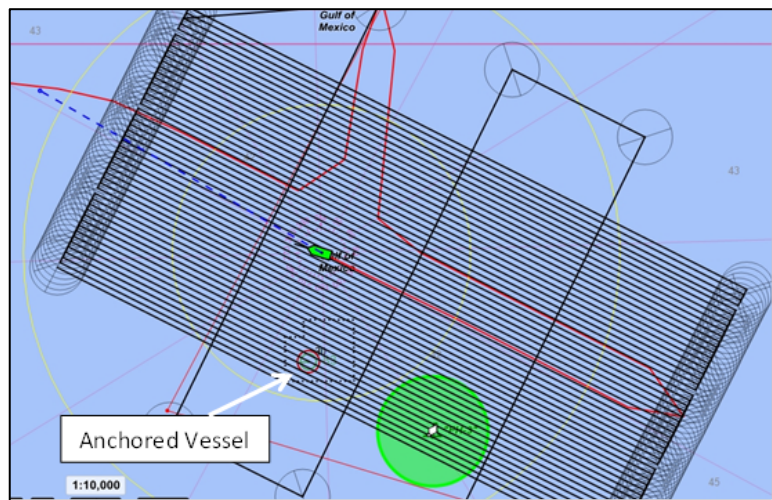

Figure 5. ISS-2000 Real-time Displays

The autonomous COLREGs engagement and keep-out radii were configured based on the *R/V Pathfinder's* size, speed, maneuverability, and mission. For the *R/V Pathfinder* conducting hydrographic survey, a COLREGs engagement radius was set to 1000 meters with a keep-out radius around the vessel set to 500 meters. Therefore any vessel traffic entering within a 1000-meter radius of the *R/V Pathfinder* would trigger the vessel control system to initiate an appropriate COLREGs maneuver response. If vessel traffic is projected to enter within a 500-meter radius, the *R/V Pathfinder* would initiate an appropriate avoidance maneuver response.

GoMOD Survey Results

Over the two days of surveying for the GoMOD on-water demonstration, 9.5 hours of bathymetric survey data (42.5 linear nautical miles) were collected, 86 SSP casts were taken, and there were six COLREGs engagements, of which three were real-world vessel encounters and three were simulated injected interferers (used for testing behavior).

During the first day of data collection there were no vessels in the survey area. Therefore, Leidos injected a simulated interferer to force a COLREGs engagement. A bow-to-bow meeting was established using a simulated interferer, and once the virtual vessel reached the 1000-meter COLREGs engagement threshold, the *R/V Pathfinder* entered into an avoidance maneuver, allowed the vessel to pass, and then resumed the survey line. A gap of 100 meters in coverage was created as a result of this maneuver.

On day two of the GoMOD survey there were two fishing boats in the survey area which allowed for real world COLREGs interactions. The first interaction was with a fishing vessel which entered the survey area and anchored. The vessel was initially seen as a moving target and the *R/V Pathfinder* reacted appropriately and maneuvered allowing the vessel to be the stand-on vessel. Once the COLREGs state was resolved, the *R/V Pathfinder* returned to the survey line. The path planner was configured for a 150-meter stand-off for stationary objects; therefore on the next survey

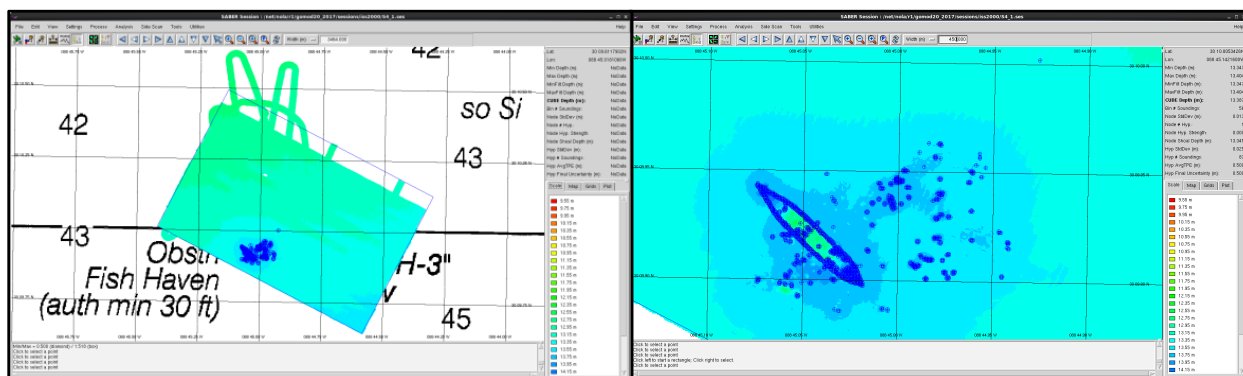**Figure 6. *R/V Pathfinder* Passing by a Vessel at Anchor**

line, the *R/V Pathfinder* maintained the survey line as it passed by the anchored vessel (**Figure 6**).

After completion of the GoMOD demonstration, all hydrographic data were run through Leidos' standard hydrographic data post processing pipeline, using the Leidos Survey Analysis and area Based Editor (SABER) product. Processing included the application of final correctors, removal of fliers, application of total propagated uncertainty (TPU), production of final gridded surfaces, and analysis of junctions between the GoMOD survey data and available historic hydrographic data. GoMOD data were corrected using water levels obtained from NOAA tide station 8747437

(Bay Waveland, Mississippi) using water level zoning obtained from the Naval Oceanographic Office (NAVOCEANO).

The one-meter CUBE surface met International Hydrographic Organization (IHO) 1a standards with the only nodes exceeding the IHO Order 1a allowable uncertainty for the observed water depths (at 95% confidence level), being associated with the wreck or debris around the wreck (**Figure 7**). Depth differences between the cross line and mainscheme data were within 0.11 meters 96% of the time, which was well within the IHO Order 1a maximum allowable vertical uncertainty (0.527 to 0.531 meters), for water depths of 12.728 to 13.651 meters. In addition, a junctioning survey from 2013 (NOAA Registry # H12355) was downloaded from NOAA's National Centers for Environmental Information (NCEI) website and depth differences were within 0.015 meters 96% of the time.

Figure 7. GoMOD Depth Surface Illustrating Nodes That Exceed IHO Order 1a Allowable Uncertainties Associated with Features (Blue symbols)

Advanced Naval Technology Exercise 2017 (ANTX 2017) Survey

In preparation for the ANTX 2017 survey efforts, the vessel control system and survey data control systems were enhanced to add an additional path planner specifically for line-following, running in parallel with the COLREGs obstacle avoidance path planners. A new component was added to pass control of the vessel between the line-following path planner and the COLREGs obstacle avoidance path planner, as required based on priority.
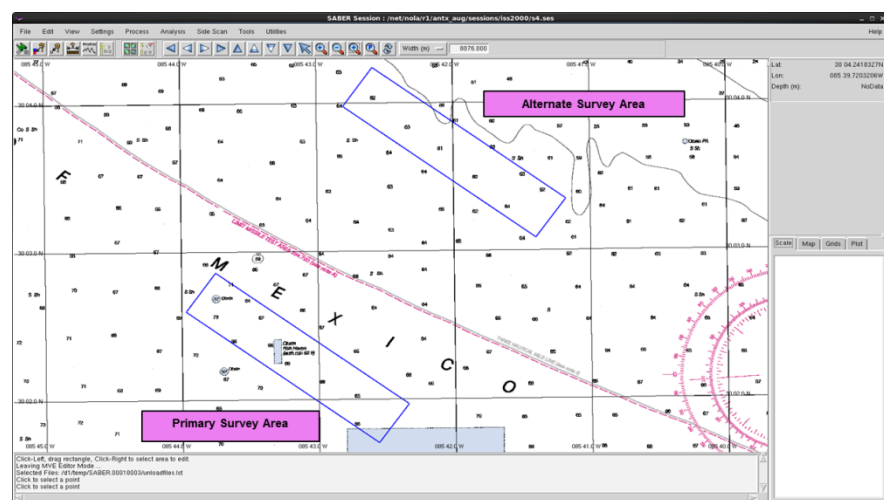
The autonomous vessel control system was updated with the addition of the line-following path planner and incorporated a look-ahead waypoint approach instead of the previous fixed waypoint approach. Now as the vessel progresses along the pre-defined survey line, a virtual look-ahead waypoint is continuously projected along the line between the vessel and the line's end waypoint. The lead distance for the look-ahead waypoint projected in front of the vessel is configurable and was set to 25 meters for ANTX 2017. Once the vessel enters a COLREGs engagement or must maneuver around a fixed contact, charted obstruction, or user pre-defined keep out area, the vessel would have a look-ahead waypoint continuously re-projected along the survey line to return to once the avoidance state has cleared. This approach resolved the issue of collocated waypoints and identified keep out areas, as observed when using the intermediate waypoint method.

Also, a new Survey System Monitor program was incorporated into ISS-2000 to allow monitoring of the survey system health. When a given system's data are outside predefined parameters, the monitor program issues a warning to remote monitors. A Weatherpak 2000 environmental monitoring system was also integrated into ISS-2000 to record and report real-time weather conditions, while two live camera feeds provided situational awareness from remote locations.

ANTX Operational Scenario

Survey operations for ANTX 2017 took place over a four day period spanning 12-16 August 2017 with official survey demonstrations taking place 14-16 August 2017. Two radio systems were utilized to allow for remote monitoring and control of the system, if required: 1) a Leidos developed software defined radio with integrated mobile adhoc network (MANET) software; and 2) a Kongsberg marine broad band tactical radio (MBR). The radio systems sent interactive displays of the various onboard systems to shore locations. Due to restrictions at NSWC, the shore site was located at a remote location in Panama City, Florida. From there the data were transmitted to both the NUWC Newport, Rhode Island site and the NSWC Panama City, Florida site using cellular technology. This allowed both Newport and Panama City sites to have real-time visualization and interactive capabilities of the vessel's onboard displays and systems.

There were two separate ATNX survey areas identified approximately 7.5km south of the Panama City harbor (**Figure 8**). The primary survey area was selected due to known seafloor objects such as sunken bridge spans, wrecks, and debris which would provide interesting features for hydrographic survey data collection. An alternate area was chosen 2.5km northeast in the event vessel traffic in
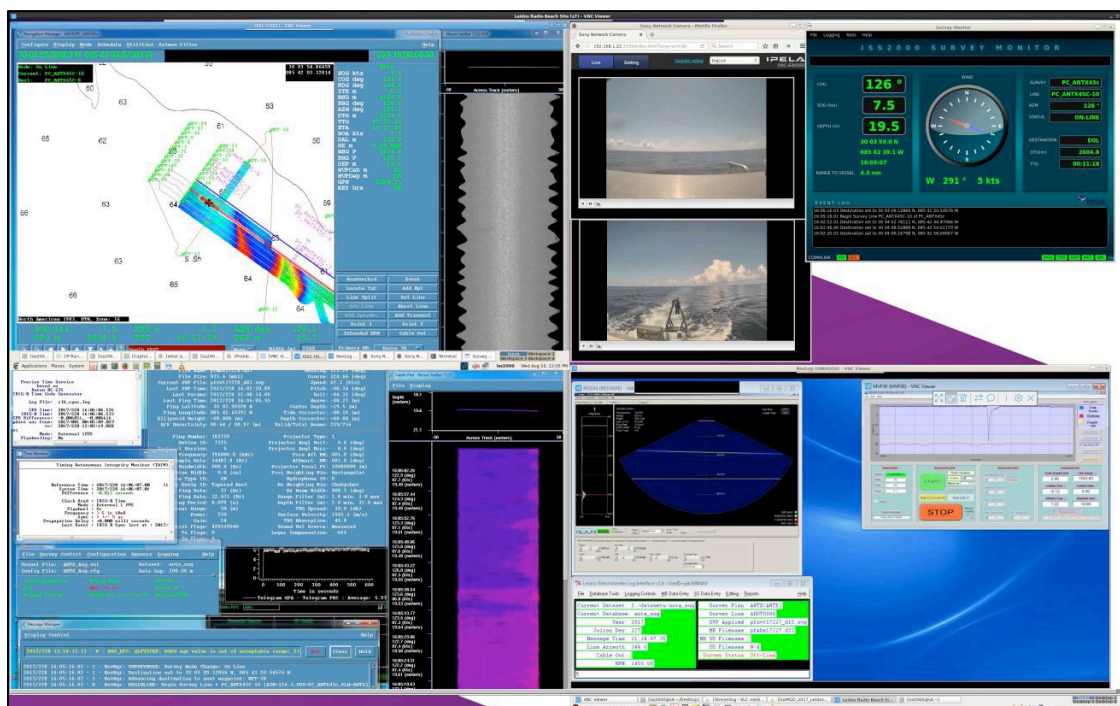

Figure 8. Primary and Alternate Survey Areas (Blue Rectangles) off the Coast of Panama City, FL

the primary area impacted the ability to collect a meaningful and contiguous bathymetric dataset.

The ANTX operational scenario followed the same general model utilized in the GoMOD survey. The *R/V Pathfinder* transited from NSWC Panama City to the RW "SA" Mo (A) sea buoy under manual control. Once at the sea buoy, *R/V Pathfinder* crew deployed the MVP30 SSP towfish, activated vessel autonomy, and initiated auto deployments of SSP casts. Under autonomous control, the vessel completed the remaining transit to the first assigned survey line and commenced survey operations. The crew onboard the *R/V Pathfinder* were hands off of both the vessel and survey controls, once the autonomy mission was enabled.

In parallel with the autonomous survey effort, Leidos transmitted vessel and survey data to both the NSWC Panama City Leidos booth, and NUWC Newport Leidos booth, using one of two independent communication paths: the Leidos MANET or the Kongsberg MBR. From each of the remote sites, personnel were able to display and monitor the survey data acquisition control system status, data quality, and survey mission progress (**Figure 9**). In addition, the communication links provided remote control of the survey data acquisition systems. Remote control of the survey systems was limited to demonstrating the capability, and not for controlling functions resulting from a lack of autonomous capability.
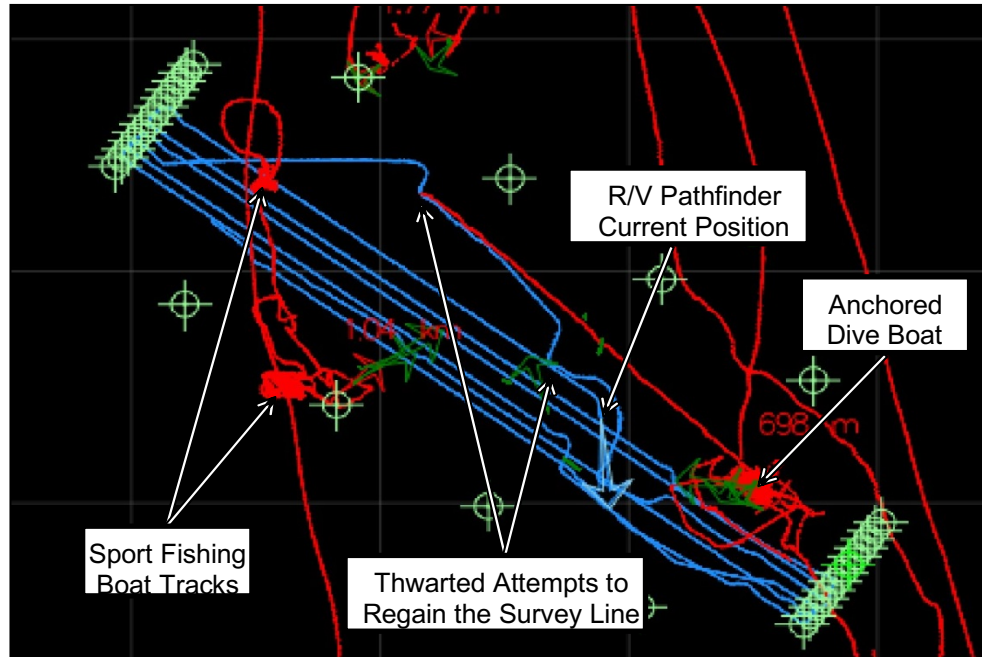

Figure 9. Remote Desktop Display in Newport, RI and Panama City, FL, Showing Live Data Feed From *R/V Pathfinder* during Autonomous Survey Acquisition Offshore
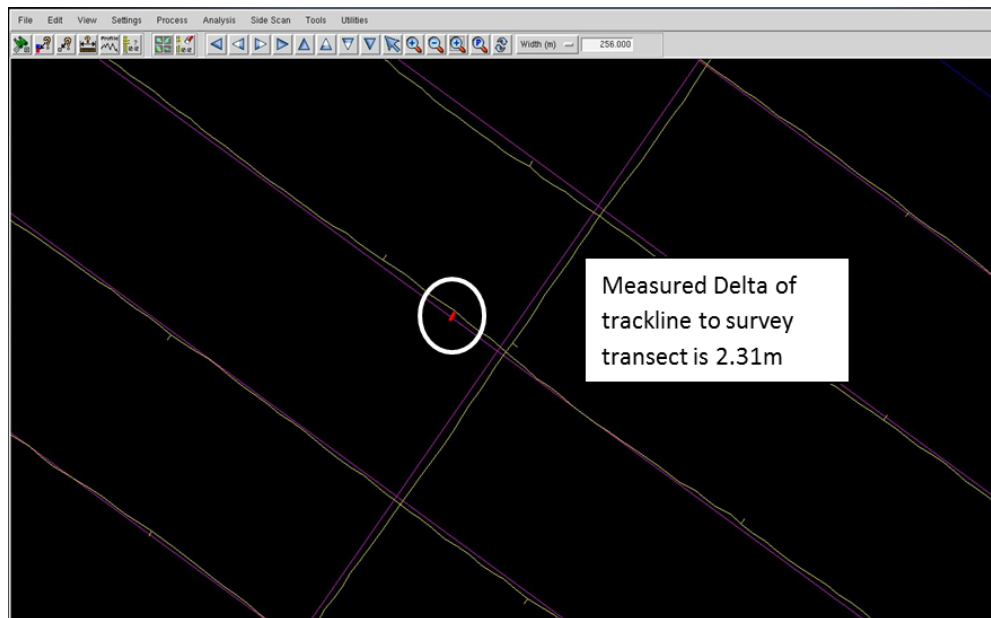
ANTX 2017 Survey Results

As expected, the vessel traffic in the primary survey area was plentiful as illustrated in **Figure 10**. While this allowed the *R/V Pathfinder* autonomy systems to demonstrate a variety of COLREGs maneuvers and avoidance of stationary obstacles, it hindered the collection of a coherent bathymetric dataset. As a result, Leidos choose to balance survey operations between the primary and secondary areas to collect a more complete bathymetric dataset within the allowable demonstration timeframe. While there were no naturally occurring interferers encountered within the alternate survey area, Leidos injected virtual interferers, simulated in real-time, to demonstrate proper maneuvering responses of *R/V Pathfinder* from the autonomous vessel control system.

During the ANTX 2017 demonstration, 63.05 linear nautical miles (lnmi) of online data were collected within approximately 15 hours of survey effort. There were 23.34lnmi (43.22km) of

online data collected within the primary area and 39.71lnmi (73.55km) in the alternate area. A total of 37 SSP casts were taken and applied to the multibeam data. The *R/V Pathfinder* was able to maintain line-following within ±2.5 meters cross track error when not engaged in a COLREGs maneuver, and with observed 15-20kt winds and 2-3ft broadside seas (**Figure 11**).
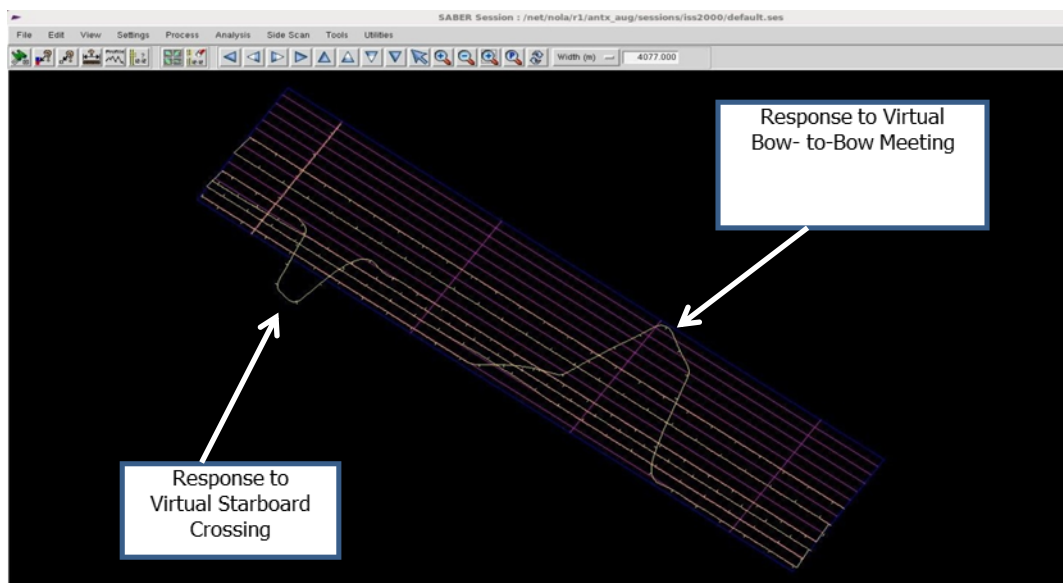

Figure 10. Survey Progress being Challenged by Sport Fishing Boats and an Anchored Dive Boat in Primary Survey Area
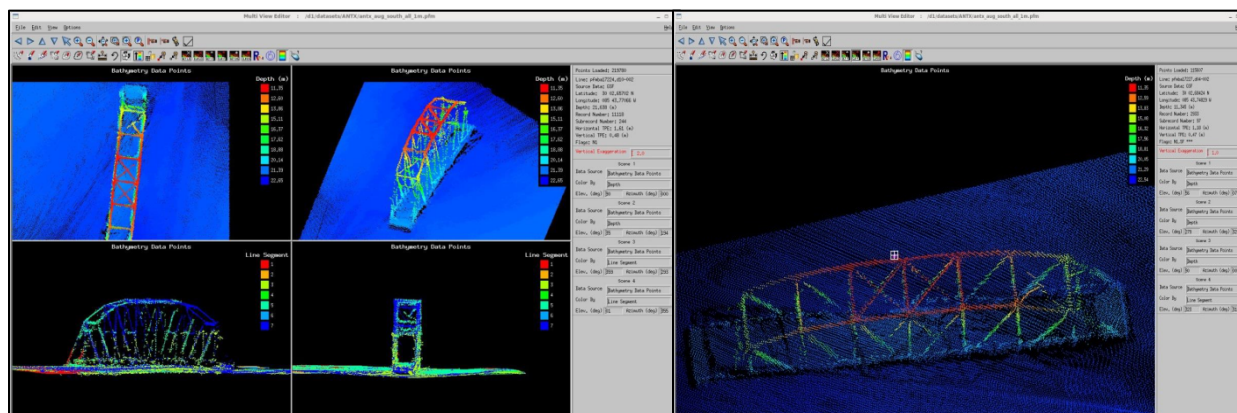

Figure 11. Survey Line (Magenta) and Vessel Track-line (Yellow) Illustrating Line-Following of +/- 2.5 Meters

There were 22 COLREGs maneuvers resulting from a combination of real vessel traffic and injected virtual interferers. **Figure 12** illustrates the primary survey tracklines with two autonomous COLREGs maneuvers to highlight the balance between maneuvering and survey.

Figure 12. Survey Line (Magenta) and Vessel Trackline (Yellow) Illustrating COLREGs Maneuvers

After completion of the ANTX 2017 demonstration, all hydrographic data were run through Leidos' standard data post processing pipeline using the Leidos SABER product. The ANTX data were corrected using water levels obtained from NOAA tide station 8729108 (Panama City, Florida) using historical zoning downloaded from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) website. The hydrographic data collected during the ANTX 2017 survey were of high quality, meeting IHO Order 1a standards. Representative images of the bathymetry data are provided in **Figure 13**.
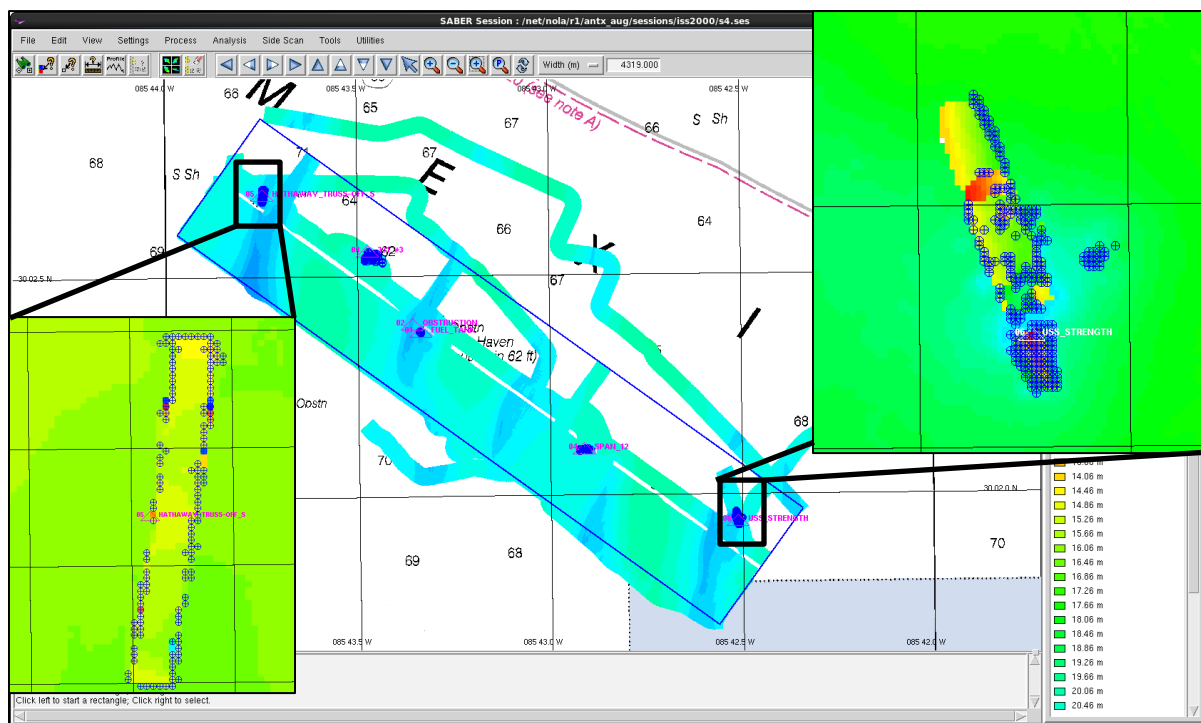

Figure 13. Bathymetry Data of a Bridge Span within the Primary Survey Area

Analysis of the junction data showed that depth difference values between the ANTX 2017 cross line and mainscheme data were within 0.11 meters 96.46% of the time for the primary area, and were within 0.09 meters 95.71% of the time for the alternate area. This is well within the IHO Order 1a maximum allowable vertical uncertainty of 0.566 to 0.581 meters for the primary area (CUBE depths ranging from 20.457 to 22.693 meters), and 0.556 to 0.571 meters for the alternate area (CUBE depths ranging from18.635 to 21.262 meters).

In addition, junctioning hydrographic survey data were downloaded from NOAA's NCEI website and compared with the ANTX 2017 data. NOAA Registry # H12718, collected in 2015, covered the northwestern half of the ANTX 2017 primary area. Depth differences between the two surveys showed that the depths agreed within 0.016 meters 95.92% of the time.

Within the primary and alternate survey areas the only nodes that exceeded the IHO Order 1a allowable uncertainty (95% confidence level), were associated with features observed on the seafloor (**Figure 14**) which is to be expected.

Figure 14. ANTX 2017 Depth Surface Illustrating Nodes That Exceed IHO Order 1a Allowable Uncertainties Associated with Features (Blue symbols)

Conclusions

During the Gulf of Mexico Unmanned Systems Operational Demonstration (GoMOD) and the Advanced Naval Technology Exercise 2017 (ANTX 2017), Leidos made numerous advancements in autonomous surface vessel mission capability, including successfully demonstrating the following:

1. The ability to remain COLREGs compliant in a target rich environment while collecting IHO Order 1a hydrographic survey data for a predefined survey mission
2. The ability to collect fully corrected survey data in real-time in a fully autonomous mode
3. The ability to remotely view and control data collection from remote sites with the use of two different types of radios
4. The ability to maintain a survey line within ±2.5m with 15-20kt winds and 2-3ft seas on the beam, and the ability for the vessel to return to the survey line after a COLREGs engagement, limiting gaps in coverage consistent with gaps created by crewed vessel operations