Simultaneous Operation of Heterogeneous AUVs

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***Abstract*–This paper discusses the experiences of operating two AUVs in parallel and the modifications to equipment and protocol to make these operations possible. The two AUVs include a low-altitude, hovering, photo survey vehicle and a broader-coverage sonar mapping vehicle. At the expense of operational and technical complexities, these two vehicles and their support equipment have been operated together in order to make efficient use of available ship time.**

***Keywords*—multiple AUVs; seafloor survey**

I. INTRODUCTION

Single AUV operations can be adventures in themselves, while multi-AUV operations add a whole new set of engineering challenges and operational hazards. A multitude of papers consider the combined use of identical or at least similar vehicles. These papers range from field observations to fantastic theoretical simulations. Much of this research is driven by the military application of mine detection and incorporates inter-AUV communication, an area not yet considered by this research. By contrast, this use of multiple AUVs stems from the need to acquire both broad acoustic surveys and focused photosurveys efficiently within the available ship time.

Also contrasting with multi-AUV research involving identical vehicles, this paper presents an odd couple of AUVs working together: the flight-style Eagle Ray, and the hovering Mola Mola. The former collects multibeam data from 20 to 50 meters above the seafloor and can travel 180 kilometers in a single 30 hour mission. The latter collects photo coverage of the seafloor at an altitude of 3 meters, covering a 60 meter by 60 meter block in a single survey.

The advantage of multi-vehicle operations in this context is that data collection can be maximized during limited ship time and weather windows. Previously the two vehicles were operated in sequence, deploying one while the other was charging. Since the vehicles have drastically different mission times, the inefficiency of this scheme was immediately obvious. Still, serial operation is necessary when a vehicle's mission is dependent on data from its counterpart's survey.

One challenge of multi-vehicle operations is personnel limitations. In this work, the same team operates both vehicles. A second challenge is the management of support equipment for the two vehicles. In this case, some subsystems, such as the acoustic tracking equipment are shared, while the launch and recovery methods and various

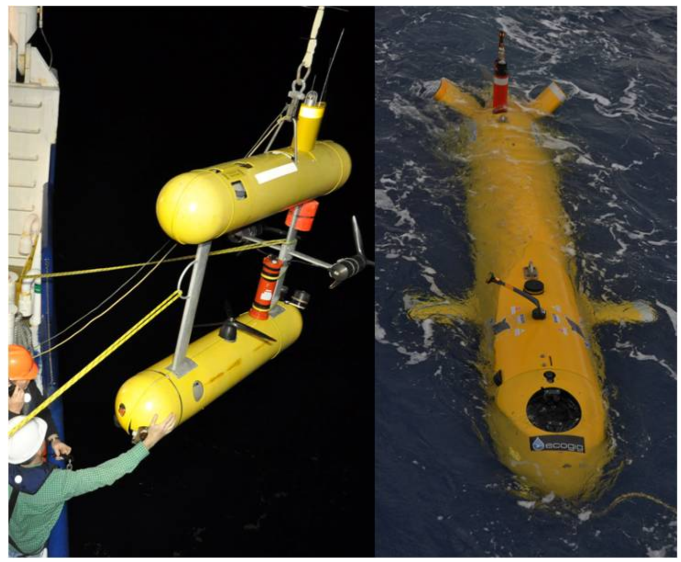

Figure 1. Mola Mola being launched and Eagle Ray readied for recovery

communication and navigation systems are are unique to each vehicle. Another challenge comes from the times when an “autonomous” underwater vehicle requires operator intervention, whether from typical mission behaviors or due to anomalies.

The personnel operating Eagle Ray and Mola Mola multitask between vehicle launch and recovery, auxiliary deck operations, vehicle maintenance and repair, and control room operations. After recovery some of the same personnel add data processing to their other tasks. An operator is always present at the control station when either vehicle is in the water. Depending on the ship, 24 hour deck operations may not be possible, regardless, some intensive tasks – like Eagle Ray recovery – are simply not carried out at night unless absolutely necessary.

Sometimes AUVs demand operator interaction. Both vehicles are monitored closely during descent and into their first survey line. This is when most faults have been observed. Depending on the navigation scheme being used and the operational depth, a position fix may need to be sent acoustically to either of the vehicles before they begin their surveys. If an anomaly is detected by acoustic communication or the tracking shows an errant path, then the submerged vehicle may require interaction from the operator. If the vehicle is out of acoustic range and responds to a fault, the

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operator may then receive communication from a vehicle unexpectedly on the surface. When these issues occur during a multi-vehicle operation, they must be prioritized to a certain basis in order to determine a proper course of action.

II. The NIUST AUVs

The AUVs share a common tracking system, which simplifies multi-vehicle operations. A LinkQuest TrackLink 5000HA ultra-short baseline (USBL) system is used to acoustically track the vehicles. This shipboard equipment interrogates a transponder on each vehicle in turn, and the vehicle transponders each respond back with a tracking ping. Eagle Ray also uses this system for acoustic communication. Commands can be sent with the interrogation, and acoustic data can be returned after the tracking response. Mola Mola requires a separate WHOI Micromodem system for acoustic communication and also determines its range to navigation beacons using the Micromodem.

While near the ship, Eagle Ray can communicate through a 900 MHz wireless ethernet link. Mola Mola also uses the 900 MHz band, but for a wireless serial protocol. The vehicles both use Novatech beacons to provide a backup means of locating them after surfacing. They use a strobe, VHF beacon, and Argos transmitter. The Argos signal is detected by satellites, and the vehicle position is updated on a website with a delay around 30 minutes. Since Eagle Ray is capable of traveling a greater distance from the survey area if it becomes lost, it is equipped with an Iridium satellite modem. The previously mentioned beacons are individually battery powered, but the Iridium system is powered by the vehicle and is integrated with its control computer. If Eagle Ray surfaces and is outside of the range of its 900 MHz link, it will initiate a call to the Iridium transceiver in the shipboard control station.

Vehicle endurance plays a key role in the timing of parallel operations. Eagle Ray can survey for nearly 30 hours, while Mola Mola's much smaller battery pack limits its operations to 8 hours maximum. Each vehicle must be monitored for roughly the first hour of its mission. Both vehicles utilize inertial navigation systems (INSs) with acoustic aiding. After reaching an altitude of 50 meters off the bottom, Eagle Ray's standard protocol is to run a box pattern to stabilize the navigation system until an operator command is transmitted. A position shift may be transmitted at this time if an offset is detected between the vehicle's acoustically reported position and the position derived from the USBL tracking system. Mola Mola can operate in the same fashion, accepting USBL position shifts from acoustic communication, or it can use a form of long baseline (LBL) navigation in which it interrogates seafloor transponders and infers its position from the resulting travel times.

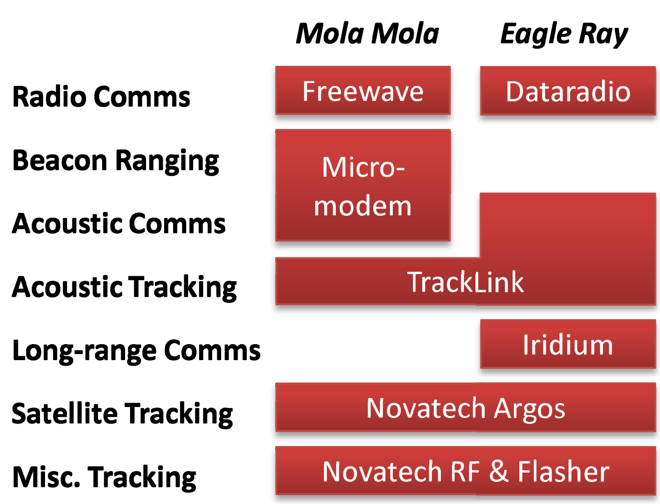

Figure 2. Mission support equipment

III. Multi-AUV Operations

This section discusses NIUST's multi-vehicle operations using Eagle Ray and Mola Mola as well as the modifications and protocols developed to support these operations. The two vehicles have been used independently on cruises, but together, they provide complementary data products. Eagle Ray requires a significant amount of deck space for its container and its launch and recovery system. Mola Mola requires little deck space and is launched and recovered using the ship's crane. It has very little additional overhead beyond what is already required for Eagle Ray operations, so Mola Mola has become a common companion to Eagle Ray cruises.

A. Setting up for Multi-Vehicle Operations

The first mission in which the two vehicles worked together was a serial operation. NIUST was performing surveys of possible shipwrecks documented by NOAA and the former MMS from anomalies in industry sidescan surveys [1]. Eagle Ray conducted initial multibeam surveys that would not only reveal the location of the target and confirm it as a shipwreck, but also determine if entanglement hazards were evident. If an "all clear" is given, then Mola Mola could dive for a low-altitude photo survey.

In 2012, the NIUST AUVs became a component of the ECOGIG consortium. ECOGIG is a project funded by the Gulf of Mexico Research Initiative (GoMRI) that studies the effects of oil and gas input into the northern Gulf of Mexico. In this project, several areas of the Gulf of Mexico have been selected for placement of seafloor landers [2] and sediment trap moorings. The task of the AUVs is to generate high resolution maps of these research sites [3]. These maps are used to guide equipment placement and serve as base maps for tethered vehicle operations. Eagle Ray's sonar data provides information about the seafloor and subbottom structure as it relates to natural oil and gas seeps. Mola Mola photosurveys provide an assessment of biological activity and details of bottom types and features. When surveying an area where a lander has already been placed, Mola Mola performs its survey around the lander itself to provide a detailed record of its surroundings. Unlike the shipwreck cruise, analysis of

Eagle Ray data is not required before launching Mola Mola. The multibeam data, however, typically indicate additional photosurvey targets.

For mission management, Eagle Ray integrates into a navigation and mission building utility, ASCA Fleet Manager. Mola Mola is controlled using a Linux command line interface, and a separate program generates and interprets its acoustic modem messages. A mission management software package called AUView is currently being written in-house. One of its current capabilities is transmitting Mola Mola's position in a format accepted by Fleet Manager. Using this somewhat convoluted system outlined in Fig. 3, mission progress can be monitored on a single map display, which is necessary for smooth multi-vehicle operations. The ship and multiple vehicle points are displayed together.

Eagle Ray is represented by three points on the screen: the position computed by its navigation system and telemetered to the ship, a tracking point computed by the USBL system, and a simulated point that simply time steps through the programmed mission tracks. If Eagle Ray is outside of communication and tracking range, the simulator continues to update, providing a rough position estimate. Likewise, Mola Mola is represented by two points: one for the USBL tracking position and one for the position reported from the vehicle computer itself. A plot of all these positions from a mission described in the following case study is shown in Fig. 4.

B. Vehicle Mission Sequence

As the vehicles descend from the surface, the USBL and telemetered positions deviate. Telemetry always indicates precisely where a vehicle's INS reports its position, which drifts significantly during descent. The USBL system produces an accurate representation of the vehicle's position that is very noisy due to effects of the signal path through the water column and error in ship motion measurements. The ship must remain in the immediate area of the vehicle during descent to monitor these positions. USBL positions can be monitored to quantify the position error, and a position update can be used to apply a correction to the drifting INS. Standard protocol is to monitor each vehicle closely until it reaches the bottom and makes its way to the beginning of the first survey line. A majority of the faults demonstrated by these vehicles occurred during this critical phase of the mission.

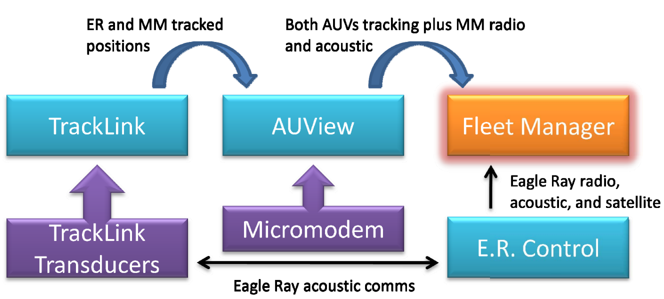

Figure 3. Feeding positions into Fleet Manager (showing acoustic systems).

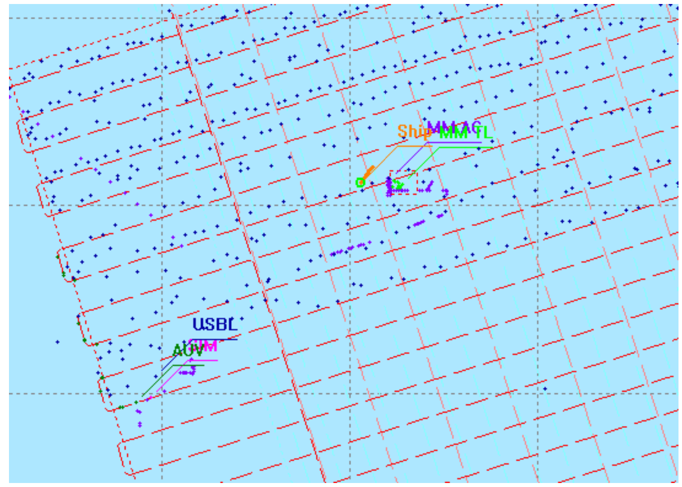

Figure 4. Tracking and telemetered positions for both AUVs in addition to ship and simulator points

After the survey starts, any major deviation between the USBL and telemetered points indicate some form of navigation or control failure, requiring operator intervention. Aside from monitoring for such failures, further gain comes from closely shadowing the vehicle during its mission. During the survey, the vehicle navigation system may drift a significant amount. A seemingly random drift occurs from integration errors of the inertial system. Systematic errors may stem from angular and scale offsets of the vehicle's doppler velocity log, which measures frequency shifts of pings off the seafloor to provide the INS with measured speeds in all three dimensions. By closely following the vehicle, the inherent noise in the USBL tracking can be minimized providing a reference to the vehicle's INS drift. Instead of following the vehicle continuously, however, offsets can be checked periodically and interpolated in post processing. This allows time for other ship operations.

C. Acoustic Beacon Navigation

As soon as Eagle Ray is surveying and its reported position matches the tracking position (or an acceptable offset is noted) then attention may be directed to Mola Mola operations. Mola Mola's navigation error can be handled with a similar protocol – offsets can be measured between the two points, and a correction is telemetered to the vehicle. One alternative is to use LBL-type navigation instead of USBL tracking. In this method, the vehicle determines its range to seafloor beacons several times a minute and uses their known positions to compute its location. To avoid navigation discontinuities (appearing as small jumps in position) during a mission, the beacon ranges are logged but not forwarded to the navigation system once the survey starts.

LBL-type navigation is convenient when multiple dives will be performed in the same area, but it requires additional overhead. Beacons may be deployed and surveyed while Eagle Ray is mapping. As a final alternative, the acoustic releases of one or more landers may be utilized in the same manner as surveyed beacons. If only one beacon is used, an additional pattern of the vehicle is needed before beginning the survey. If the vehicle is north or south of the beacon, the beacon range can constrain the northing error, and likewise for the easting error. The vehicle must therefore navigate around the beacon by at least 90 degrees to minimize navigation error before starting its survey.

While both vehicles are on survey, the ship typically maintains a watch circle around Mola Mola, which is typically well within the area of the more expansive Eagle Ray survey. An intercept course may be commanded as necessary in order to measure Eagle Ray's navigation offset as it passes. After surveying LBL beacons is another convenient time to check on Eagle Ray, while beacon positions are being computed and loaded into Mola Mola's configuration file. If Eagle Ray is outside USBL range, then its simulator track is used as the reference point. A simulated Mola Mola point is not necessary since that vehicle is currently incapable of wandering too far from its previously tracked position. If the ship must leave Mola Mola, it should simply return to the vehicle's last known USBL position.

D. Recoveries and Mission Exceptions

Anomalies should be prioritized so that an orderly protocol can be followed in the event of a malfunction of both vehicles. So far, faults are dealt with on a case-by-case basis. Vehicle faults up to now have allowed the other vehicle to continue its survey while a recovery is performed. If Eagle Ray were to surface outside of wireless ethernet range, it would call the control station over Iridium and establish a communication link. This system was modified for simultaneous operations by automating the next steps: the vehicle position is displayed on the mission management screen and its battery status is displayed on the vehicle's control GUI. Depending on the status of the Mola Mola mission and Eagle Ray's battery capacity, a decision could be made on which vehicle to recover first. The issue is that Mola Mola has a very low visible profile at the surface, short battery life, and no long-distance communication capability. Both vehicles can take roughly 30 minutes to recover depending on sea state, so the information provided over the Iridium provides sufficient information to assess urgency.

If both vehicles will be on the surface at the same time, either by anomalies, intervention, or mission completion, then priority should be given to recovering Mola Mola for the same reasons given above. Eagle Ray can be remotely piloted at the surface, but that capability has not yet been developed for Mola Mola. The exception to the recovery order is that if Eagle Ray has a low battery capacity then it should be recovered first. Its typical recovery process includes several maneuvers and the release of a float to spool out a length of recovery line. Recovering this vehicle unpowered is a challenge, while Mola Mola has been recovered frequently after its batteries have been exhausted. On several occasions, Eagle Ray has been left on the surface with its battery load minimized until morning. This allows rested personnel to perform the recovery with a clear view of the vehicle and the seas.

E. Case Study

In a recent dive sequence in the Atwater Valley block 357 [3], Eagle Ray was on survey while repairs to one of Mola Mola's thrusters were being made. At the conclusion of the survey, which was run at 50 meters altitude, a target for a Mola Mola dive was found, and a region was defined for a shorter, higher-resolution (20 meter altitude) follow-up survey for Eagle Ray. Eagle Ray was launched, and after its survey was in progress, the ship moved to the Mola Mola deployment location. After it reached the bottom, USBL position corrections were transmitted as the vehicle approached the survey start point. Mola Mola was monitored throughout most of its mission (well within the Eagle Ray survey area) with only a couple departures to check on Eagle Ray status and assess any position errors. Mola Mola surfaced first, and was recovered within ~30 minutes of Eagle Ray surfacing.

Mission tracking is shown in Fig. 4, 5, and 6. Fig. 4 shows the progress of both vehicles shortly after Mola Mola started its survey lines. At this point, good agreement is seen between the Eagle Ray simulator (pink SIM), telemetered (green AUV), and tracking (blue USBL) positions. As Eagle Ray moves farther away, acoustic telemetry can no longer be received, and tracking becomes more erratic.

Tracking of Mola Mola (green MM_TL) was fairly consistent, although a 30 meter offset was present between that and the acoustically telemetered (purple MM_AC) position. Since the offset was in an acceptable direction, no further corrections were sent to the vehicle, and the offset remained fairly static throughout the survey.

Fig. 5 shows acoustic tracking as the mission has progressed further. The range between the ship and tracked Eagle Ray position is indicated. Although the USBL point is reasonable for the update shown in the figure, most updates at this range are unusable.

Fig. 6 shows the ship track throughout the multi-AUV survey. Eagle Ray is shown during its ascent, and the point plotted for Mola Mola is leftover from its last update before it neared the surface (preventing further tracking). The results

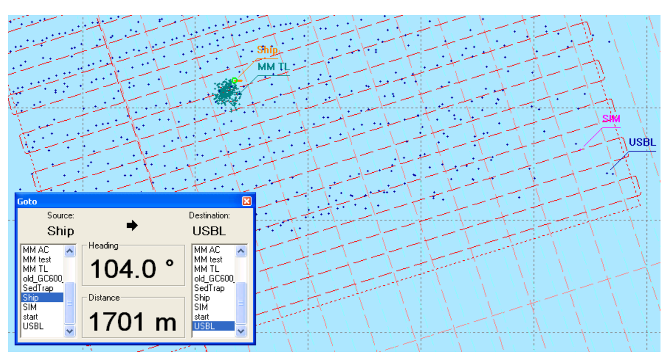

Figure 5. Acoustic tracking of both vehicles during the survey

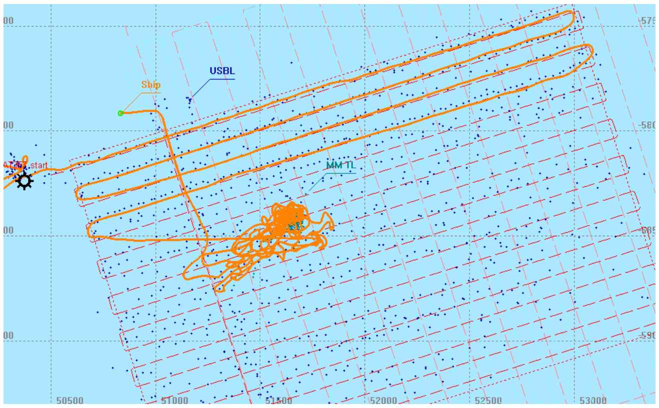

Figure 6. Ship plot and acoustic tracking throughout survey

of the survey are shown in Fig. 7, in which the Mola Mola photomosaic is plotted within a subset of the Eagle Ray bathymetric survey.

IV. Summary

Using concepts collected in this paper, multi-AUV operations have been carried out using the NIUST AUVs Eagle Ray and Mola Mola. Commonly, even with the goal of running both vehicles at the same time, component failures and the ensuing troubleshooting and repairs often lead to single vehicle operations anyway. Sometimes limitations in equipment, personnel, or knowledge of a target area prevent multi-vehicle operations as well. When the weather and vehicles are both cooperative, the methods above have allowed the NIUST vehicles to collect survey data quickly and efficiently.

Acknowledgments

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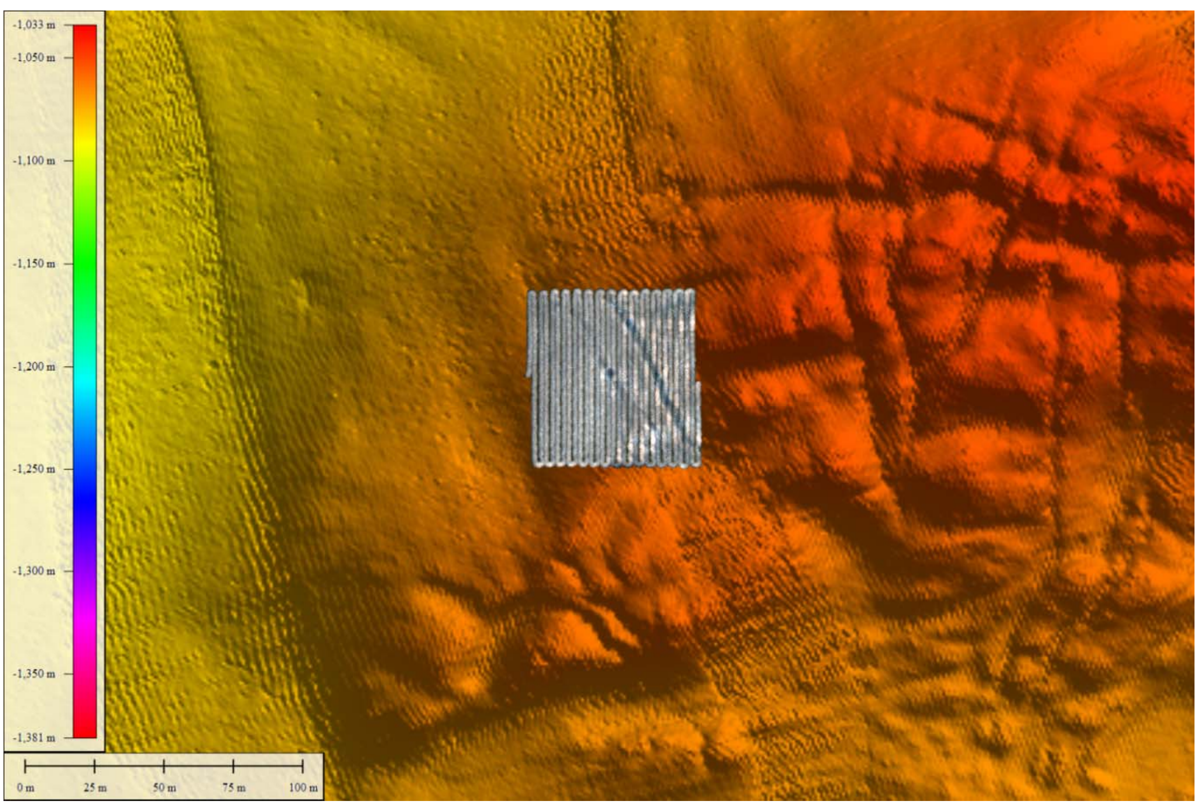

Figure 7. Results of multi-AUV operation with photomosaic overlay (GoMRI data identifier R1.x132.137:0029) on bathymetry (GoMRI data identifier R1.x132.137:0029)