Robot-Assisted Bridge Inspection after Hurricane Ike

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Abstract —The Center for Robot-Assisted Search and Rescue (CRASAR®) deployed the custom Sea-RAI man-portable unmanned surface vehicle and two commercially available underwater vehicles (the autonomous YSI EcoMapper and the tethered VideoRay) for inspection of the Rollover Pass bridge in the Bolivar peninsula of Texas in the aftermath of Hurricane Ike. A preliminary domain analysis with the vehicles identified two key tasks in subsurface bridge inspection (mapping of the debris field and inspecting the bridge footings for scour), three research challenges (navigation under loss of GPS, underwater obstacle avoidance, and stable positioning in high currents without GPS), and possible improvements to human-robot interaction (having additional display units so that mission specialists can view and operate on imagery independently of the operator control unit, incorporating 2-way audio to allow operator and field personnel to communicate while launching or recovering the vehicle, and the inclusion of teleoperation as the backup mode for autonomy). An additional research question is the cooperative use of surface and underwater vehicles.

Keywords: *rescue robotics, unmanned marine vehicles, autonomous surface vehicle, unmanned underwater vehicle*

Fig. 1. The Sea-RAI operating around the Rollover Pass Bridge.

I. Introduction

While hurricanes are associated with large scale search and rescue activities on land, inspection of coastal littoral regions is also important. Bridges must be inspected, as they are needed for responders and recovery workers to have access to affected areas, and because they influence the general recovery of the area. Seawalls, levees, or dikes may be compromised and create a secondary disaster such as seen in New Orleans at Hurricane Katrina. Channels must be restored and docks repaired as part of the economic recovery and restoration of shipping.

This paper describes the use of surface and underwater unmanned marine vehicles (UMV) for post-disaster bridge inspection by the Center for Robot-Assisted Search and Rescue (CRASAR®) in the aftermath of Hurricane Ike. CRASAR®is a center at Texas A&M that promotes robots for emergency response and sends out volunteer teams of scientists and robot manufacturers to disasters to assist and collect data, similar to tornado storm chasers and Doctors Without Borders. Hurricane Ike was a Category 4 storm that struck Galveston, Texas on September 13, 2008. The Rollover Pass bridge on the adjacent Bolivar peninsula, a major artery to the area, was severely damaged. In December, 2008, the Texas Transportation Institute (TTI) and the Texas Department of Transportation permitted CRASAR®to test UMVs for bridge inspection. In particular, the agencies wanted an evaluation of how well the Sea-RAI unmanned surface vehicle (USV) could inspect the bridge footings for scour (erosion and separation from the bottom) and map the debris field around the bridge (i.e., is there debris likely to be pushed into the substructure and damage it). The Sea-RAI at the Rollover Pass Bridge is shown in Figure 1.

As described in [1], the inspection of the underwater portion of a bridge, called the substructure, is currently done with manually with divers who must work in high currents, low visibility, and debris to physically see and touch damage. Manual inspection puts the divers at risk and is not efficient, for example due to the tidal currents at the Rollover Pass bridge, divers could only work for 15 minutes at the change of each tide. CRASAR®showed the efficacy of unmanned surface vehicles (USV) in 2005 at Hurricane Wilma [2] for determining scour and locating debris, providing a foundation for this deployment.

This paper reviews the related work on UMVs for littoral inspection, then describes the CRASAR®deployment. The deployment was successful both in terms of meeting the two mission objectives but also in identifying challenges in vehicle control, multi-robot coordination, human-robot interaction, and sensing. It contributes an understanding of the post-disaster bridge inspection which can be applied to damage from natural events (e.g., hurricanes and flooding) but also to man-made incidents such as the 2007 I-35W bridge collapse in Minneapolis.

II. Related Work

Unmanned marine vehicles have not been widely used for disaster response [3], though they have been for other applications, including mapping the Great Barrier Reef [4], demining [5], inspection of cables [6], sampling sea-air interfaces [7] and sediments [8]. With the notable exception of marina mapping [9], these littoral operations do not take place in close proximity to structures or constricted areas.

The deployment at Rollover Pass bridge is an extension of previous field work and research by CRASAR®. CRASAR®conducted a survey of the Marco Island, Florid, bridge in the wake of Hurricane Wilma [2] with an AEOS man-portable surface vehicle. That work led to the Sea-RAI project which refined the AEOS platform, added navigational autonomy, and improved human-robot interfaces [10]. While as far back as 1991, UMVs have been proposed for post-disaster inspection [11], the post-Hurricane Wilma deployment is the first known application of a USV for disaster response.

III. Deployment

The six person CRASAR®team was in the field from Dec. 17-19, 2008, and was comprised of roboticists, civil engineers, and responders and three unmanned marine vehicles. The six person team consisted of two roboticists (Murphy, Steimle), both of whom had participated in the Hurricane Wilma deployment, two civil engineering professors (Hurlebaus, Medina-Cetina), a responder from the Texas Engineering Extension Service (May), which is the state agency for urban search and rescue, and a graduate student (Lindemuth). In addition, YSI sent two experts (Hall, now with AEOS, and Slocum) to use the Ecomapper UUV with CRASAR®on Dec. 18. The primary vehicle was the Sea-RAI unmanned surface vehicle, with a VideoRay tethered ROV and YSI UUV Ecomapper as secondary vehicles for experimentation. The team focused on the USV because as noted in [2], surface vehicles have

Fig. 2. Interface showing satellite imagery of the Rollover Pass Bridge with overlays of Sea-RAI camera and sonar views.

important advantages over underwater vehicles: they can be more accurately controlled and localized through GPS, they can carry a larger payload, and they can continuously broadcast data to observers in real-time.

The deployment had a primary mission for the agencies and a secondary scientific mission. The primary mission was to evaluate the utility and performance of the USV for two tasks: inspection of the bridge substructure and mapping of the debris field. The Sea-RAI was able to meet both objectives. The primary mission success was the acquisition of comprehensible underwater imagery deemed of use to the structural community. The secondary scientific mission consisted of a preliminary Viewpoint-Oriented Cognitive Work Analysis (CWA) [12] to determine how a USV might be used in the future and experimentation with the two UUVs. CWA provides a systems perspective of a work activity, in this case how UMVs would actually be used. The CWA was the basis for 1) an evaluation of technology transition potential and roadmap based on robotics, response, and civil engineering expertise and 2) an assessment of resilience in human-robot interaction.

A. Rollover Pass

The Rollover Pass Bridge is a two-lane concrete span on Texas Highway 87 connecting a 200 ft channel between the Gulf of Mexico, Galveston Bay, and the intercoastal waterway. The pass is subject to intense tides and turbidity. Figure 2 is a screenshot of the Sea-RAI interface showing two camera views of the bridge from the USV overlaid on a Google Earth imagery of the bridge from before Hurricane Ike. Rollover Pass illustrates the complexity and the amount of structures that may be present in littoral regions versus more common UMV operations in bays or the open ocean.

B. Unmanned Marine Vehicles

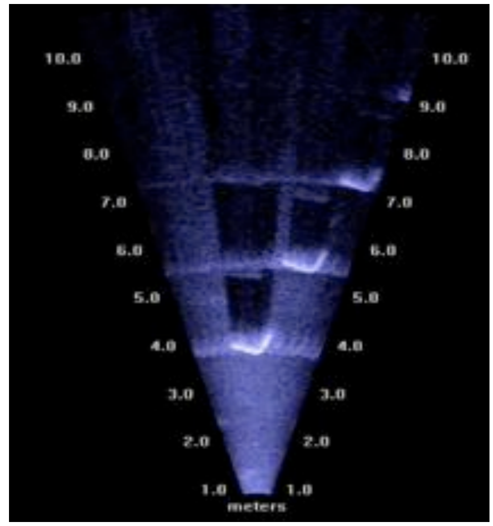
The three vehicles used at Rollover Pass are shown in Figure 3. The Sea-RAI unmanned surface vehicle is a custom

a.

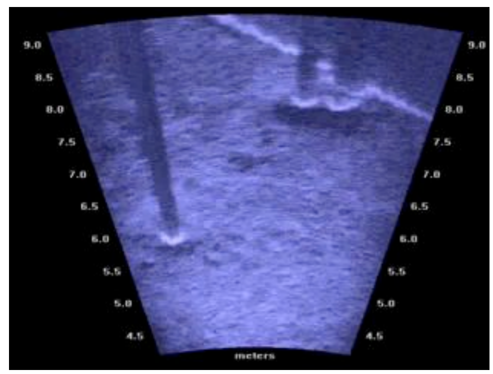
b.

c.

Fig. 3. Three UMVs used: a) Sea-RAI USV, b) VideoRay tethered ROV, and c) YSI Ecomapper autonomous UUV.



a.



b.

Fig. 4. DIDSON imagery: a.) shows no scour at Rollover Pass Bridge after Hurricane Ike, b.) shows scour (dark "holes" in front of pilings) at Marco Island dock after Hurricane Wilma.

platform based on two 6ft catamaran hulls, similar to Charlie [13] but more stable than the SCOUT [14]. It is capable of autonomous waypoint navigation and supports teleoperation. It is an adaptation of the AEOS platform built for environmental mapping. The Sea-RAI carries a DIDSON acoustic camera for subsurface inspection and a three video cameras (forward, rear, hemispherical) for viewing above the waterline. The robot can carry additional sensors. The Sea-RAI is battery powered and can operate for 4-6 hours depending on the currents. A notable feature of the Sea-RAI is that it stores sensor data and the internal state of the robot, creating a database that can be displayed in a unique Google Earth interface shown in Figure 2. Data at any point in time or location can be retrieved with a click. The VideoRay ROV and a YSI Ecomapper were also used. The VideoRay is already in use by some departments of transportation for visual inspection of bridges and debris, either lowered off a bridge or from a boat. The YSI Ecomapper carries a side-scan sonar suitable for mapping debris fields.

IV. Mission Results

The Sea-RAI was successful in meeting its primary mission objectives. The robot was deployed three times, two on Dec. 18 and once on Dec. 19 from a sand spit about 1,000 ft from the bridge. It used waypoint navigation to travel to the bridge and then was manually controlled near the bridge. Missions lasted approximately 2 hours, with about 1 hour of active investigation of the bridge and debris field in between changes in tides. The VideoRay and Ecomapper were also deployed.

The USV found no sign of scour or washout of the bridge pilings, as can be seen in Figure 4. The upper image shows the healthy pilings at the Rollover Pass Bridge. Pilings give off a bright, sharp line where the foot meets the ground. This is contrast to dark holes in the image below showing the scour at pilings for a dock at Marco Island inspected after Hurricane Wilma. The Sea-RAI also did not find debris that would obstruct navigation or present a hazard to the bridge. Figure 5 shows the typical debris scattered in the channel.

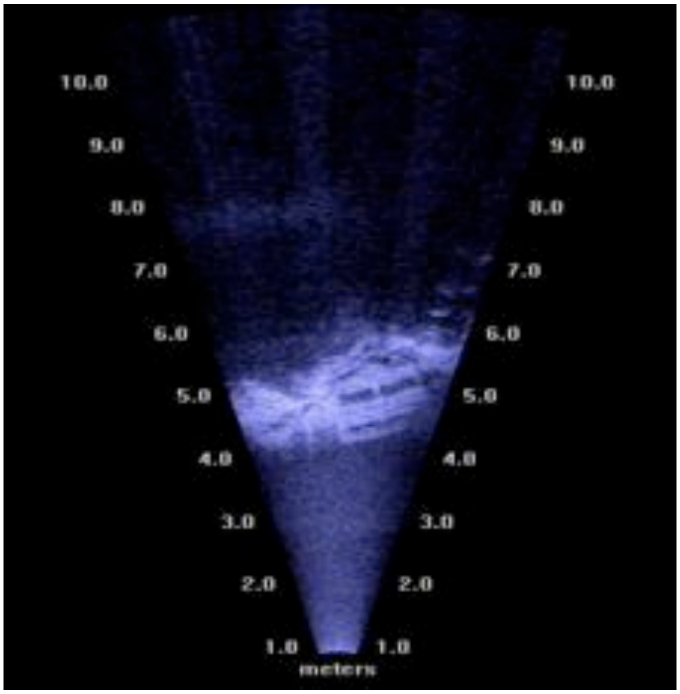


Fig. 5. DIDSON imagery: pallet in the debris in the channel.

V. General Findings

The evaluation and CWA produced findings in three areas: control challenges for UMVs, human-robot interaction, and uncertain data. The control and human-robot interaction analysis confirmed earlier findings from Wilma and other CRASAR®deployments plus observations from other marine vehicle research. The challenges in handling and fusing the sensor data is new.

A. UMV Control Challenges

The fieldwork at Rollover Pass identified three major control challenges for UMVs. The first is navigation in swift currents. The swift currents limited the times and duration the Sea-RAI, Ecomapper, and VideoRay could be used. The Sea-RAI was actually put on a safety line during the first run to make sure it could be recovered. The problems with currents and station keeping is not unknown, see [15] for another example.

The second challenge is GPS loss or errors. As noted in [2], operations near bridges interfere with GPS signals impacting the USV and the surface operations of the UUV. The Sea-RAI had to be teleoperated for the actual inspection task. The GPS loss was approximately 1% away from the bridge and 22% under or in the shadow of the bridge. Therefore GPS will not be sufficient for close inspection. And GPS errors in cluttered littoral environments can lead to collisions, as seen when the Ecomapper while using GPS for a surface-based scan of the channel bumped into a barricade.

The third challenge is obstacle avoidance for underwater vehicles, as incidents occurred in 2 of the 5 runs with the UUVs (40% incident rate). The Ecomapper could not safely operate submerged through the channel until the Sea-RAI mapped the debris; unlike bays or open water, littoral regions after a disaster may be cluttered with unmodeled obstacles. Even using GPS, it collided with a channel barricade. The tethered VideoRay ROV became tangled around a pipeline. This highlights the need for tether management and awareness of where the tether is related relative to obstacles and the robot. Recent commercial developments have created a "smart" tether which keeps up with its own position, which might solve the problem in the future.

B. Human-Robot Interaction

The fieldwork confirmed the role of humans in shared autonomy, reinforced the need for multiple displays, and illustrated the lack of resilience in design and displays.

The role of humans were *piloting*, *payload specialists* (operating the sensors), *subject matter experts* (interpreting the data), and *safety oversight*. A minimum of four people were involved. These roles relied on a close interaction between all groups. As noted above, the robot was teleoperated for a significant portion of the time and the robot was in line of sight for the entire mission.

A surprising human-robot interaction was *the need for two-way audio*, as there was always a person involved in launching or recovering the robot. At Rollover Pass, the base station was 800 ft from the launching area. Two-way audio would have permitted the operator to coordinate with the handler in the field rather than be reduced to gesturing at a camera and having the operator signal through panning or tilting and having a spare team member run back and forth.

The need for multiple displays to accommodate multiple observers was noted in [16] and the Hurricane Ike fieldwork reinforced this. Additional displays are needed for the specialists and subject matter experts and the display should be customizable. For example a civil engineer may just want to see the DIDSON output while the operator sees the complete interface which includes vehicle health, path, etc.

The deployment also showed problems with resilience and how hard it is for humans to understand what is going on with vehicles. The DIDSON was knocked out of alignment by the force of the water, causing the operators to get confused about which way it was pointing relative to the vehicle. This led to coordination challenges as the specialist had to give counter intuitive commands to the pilot to maintain views of pilings. The design of the payloads should prevent "normal" slippage and the display should provide diagnostics for confirmation of settings and positions. This has been adressed in the newest version of the DIDSON visualization software, by providing an indication of the sonar orientation relative to the vessel it is deployed on.

C. Multi-Robot Cooperation

The UMV control challenges, particularly the problems with station keeping and obstacle avoidance, suggested that USV and UUV work cooperatively. The USV could map the region sufficiently for UUV navigation. As noted in [2], the USV could also serve as a mother for a tethered ROV, seeing where the USV could not, reducing the amount of tether and risk of tangling of a ROV, and help keep overwatch on the tether.

D. Uncertain Sensor Data

The purpose of the UMVs is inspection, to observe and record; this creates challenges in sensing processing, particularly in handling large datasets and managing uncertainty. The Sea-RAI collected a continuous stream of imagery from above and below the waterline. The imagery was color video and sonar, leading to large datasets of information. Furthermore, the data had uncertainties in localization and in content due to shadows and differing viewpoints from the vehicle and DIDSON angles, presenting challenges for accurate 3D reconstruction and in understanding.

VI. Conclusions

In conclusion, the experience at the Rollover Pass Bridge showed that Unmanned Marine Vehicles have sufficient utility for immediate use in littoral inspection. While tethered ROVs have begun to be explored by transportation departments, unmanned surface vehicles appear to be more promising than UUVs because of navigability in high currents, no tether to tangle, less vulnerable to obstacles, ability to carry payloads such as acoustic cameras which can penetrate turbidity, and real-time transmission of data. Regardless of surface or underwater deployments, UMVs pose many open research questions in control (especially with GPS dropout rates on the order of 20% or higher), human-robot interaction,cooperation between surface and underwater vehicles, and handling of large data sets of uncertain sensor readings.

VII. Acknowledgment

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