A Man-Packable Unmanned Surface Vehicle for Radiation Localization and Forensics

Grant A. Wilde[1], Robin R. Murphy[1], Dylan A. Shell[1], and Craig M. Marianno[2]

Abstract— This paper describes the first known man-packable unmanned surface vehicle (USV) system designed for radiation localization, either for nuclear treaty verification or sampling after a nuclear incident. Currently, outdoor radiation sampling is done manually or by ground or aerial unmanned systems. An unmanned surface vehicle can operate in shallow nuclear facility cooling ponds and connected streams, rivers, and bays to sample without entering the facility and while maintaining network connectivity to report readings. The Challenge 1 USV is a Lutra 1.1 autonomous airboat modified to carry an UltraRadiac™. The debris-free area to survey is determined by teleoperation, then the system autonomously generates and executes a novel spiral path and sampling policy. Challenge 1 was tested for proof-of-concept at Texas A&M Engineering Extension Service's Disaster City® with a cesium-137 source placed near one shore of a pond 72 meters from the deployment point. During this test, 775 radiation readings were taken over an area of 57.61 square meters in 18 minutes. These data were used by an inverse distance weighting interpolation algorithm to produce a visual heatmap.

I. INTRODUCTION

Man packable unmanned surface vehicles can be used for nuclear treaty verification, rapid assessment of nuclear emergencies, and monitoring recovery from a nuclear accident. The first use of a nuclear weapon during warfare was on August 6, 1945, when the United States dropped a uranium fission bomb over Hiroshima, Japan. According to Kristensen and Norris, since the first use of a nuclear bomb, the United States, Russia, the United Kingdom, France, China, India, Pakistan, Israel and North Korea possess approximately 17,200 nuclear weapons [1]. Beginning in 1963 with the Partial Test Ban Treaty and continuing through the 1996 Comprehensive Test Ban Treaty, there have been treaties pushing for the disarmament and reduction of nuclear stockpiles. As an alternative to cooling towers, nuclear warhead producing facilities are often in close proximity to a cooling pond. Cooling ponds are used instead of direct discharge of heated water to a nearby river or bay. This provides an opportunity for unmanned marine vehicle (UMV) systems to facilitate inspectors in determining through radiation sampling whether a certain facility is in fact dismantling warheads or creating warheads without having to physically enter the site. UMVs can also be used during nuclear emergencies. For example, the explosion at the Chernobyl nuclear facility on April 26, 1986, released large quantities of nuclear fuel and radionuclides from the fission products that were being created. Chernobyl used cooling ponds which provide a means of radiation sampling without entering the facility. UMV sampling would not be possible in all cases, consider that the Fukushima Daiichi plants used cooling towers and pumped water to the sea.

This paper describes the creation of a UMV boat that can be carried by one person, called a micro unmanned surface vehicle (USV), for radiation sampling in shallow littoral areas such as cooling ponds, rivers, or bays. A USV offers advantages over other types of unmanned marine vehicles. Unlike an autonomous underwater vehicle, a USV can operate in shallow water of less than 15 cm depth and maintain network connectivity for control and data sampling. A USV does not require a tether, like a remotely operated marine vehicle (ROV), which would limit the distance and mobility. However, a USV operating in shallow littoral areas poses several challenges. Navigation is a challenge since rivers and bays may have semi-submerged obstacles and there may be no depth maps; the approach taken in this paper is to let the operator specify a safe area of the water by visual inspection and then the USV autonomously creates a path to optimally sample the collision free area. Navigation is also a challenge because of platform dynamics–the USV we describe is a non-holonomic vehicle; this paper explores spiral paths rather than boustrophedon paths. Another challenge is the quality of sensing. Radiation sensing is noisy and thus a reading at a single point may not reflect the overall radiation. In practice, areas are sampled rather than a single point, but the noise in the point values within the sampled area produce a survey with widely varying numbers and are difficult for humans to interpret. This paper implements an inverse distance weighting interpolation algorithm to produce a visual heatmap that reliably portrays the smoothed data.

II. RELATED WORK

Unmanned surface vehicles are not new platforms to the field of robotics. Various post World War II USV projects were mainly used as gunnery and missile target systems [2]. Since the early 1990s, USV systems have garnered more attention by the United States Navy, whose main focus is on littoral warfare and anti-terrorism missions [3]. The first documented use of a surface vehicle in emergency response was by Murphy et. al. in 2005 when the Center for Robot-Assisted Search and Rescue deployed an iSENYS unmanned aerial vehicle (UAV) and a prototyped AEOS-1 USV to survey the damaged inflicted by Hurricane Wilma [4]. The

[1]Grant A. Wilde, Robin R. Murphy, and Dylan A. Shell are with the Department of Computer Science and Engineering at Texas A&M University, College Station, TX 77843, USA [gwilde1, murphy, dshell]@cse.tamu.edu

[2]Craig M. Marianno is with the Department of Nuclear Engineering at Texas A&M University, College Station, TX 77843, USA marianno@tamu.edu

1.9 m x 1.2 m (length x width) USV was used to detect damage to sea walls and piers, locate underwater debris, and determine safe regions for sea navigation.

Research interest in surface vehicles has focused on larger USVs, with micro-USVs having received comparatively little attention. Researchers at Carnegie Mellon's Robotics Institute have developed the Cooperative Robotic Watercraft (CRW)[5]. This surface vehicle has been released as a commercial product in the form of the Lutra Airboat which was the the data collection platform used in this paper. The CRW can be equipped to take physical samples or measure other water characteristics such as depth, pH levels, electrical conductivity, temperature, and dissolved oxygen. Hydronalix has developed EMILY (Emergency Integrated Lifesaving Lanyard) [6]. This 11.34 kg (25 lbs), jet propelled robot equipped with a flotation device can be used to rescue victims in deep, rough waters.

Unmanned ground vehicles were first used for radiation forensics and localization in Japan at the 2011 Fukushima Daiichi Nuclear Power Plant accident [7], [8], [9]. At the Fukushima Daiichi accident, robots were used to assess the damage both indoors and outdoors, conduct radiological surveys, and help with cleanup operations [7], [9]. A QinetiQ Talon combined with a gamma radiation camera were used to localize pieces of radiological material that needed to be removed from the areas around the reactors [8]. Small unmanned aerial systems (SUAS) were deployed for the first time to a radiological disaster at the Fukushima Daiichi Nuclear Power Plant as well [10]. Two Honeywell T-Hawk unmanned aerial vehicles were used to conduct radiological surveys and assess structural integrity of buildings. Kochersberger et. al. equipped an Aeroscout B1-100 SUAS with a radiation spectrometer payload used to determine gamma radiation intensity and spectrum [11]. This system was also tested with an unmanned ground vehicle that was capable of taking physical samples. No micro unmanned surface vehicles equipped with radiological sensors has been used for radiation localization.

III. Implementation

The Challenge 1 USV is a commercially available Lutra 1.1 platform modified to carry a Canberra UltraRadiac^{TM}-Plus Personal Radiation Monitor, commonly used by hazardous materials teams and nuclear inspectors. The key software modules for Challenge 1 were the spiral path planning algorithm and the inverse distance weighting interpolation algorithm used to produce a visual heatmap.

A. Lutra 1.1 and UltraRadiac^{TM} Platform

The micro USV used for the data collection vehicle was a Lutra 1.1 autonomous airboat purchased from Platypus, LLC. This surface vehicle has a rudderless design that uses a brushless motor actuated by a servo for propulsion and steering. This design for the USV was chosen due to the absence of underwater propellers. Underwater propellers would limit the micro USV to deep waters that are free of algae or other plants residing at or just below the surface of the water. Since the intended environment in which radiation readings would be collected is mainly in shallow, littoral water, the Lutra 1.1 was the best candidate for the data collection vehicle. The Lutra 1.1 weighs 6.35 kg (14 lbs) with dimensions of 90 x 50 x 45 cm (L x B x H), has a max thrust of 8 N, and has a runtime of 4-8 hours on one battery. However, the payload for the USV can be no more than 2.27 kg (5 lbs). An image of the Lutra 1.1 can be found below.

Fig. 1: The Lutra 1.1 Autonomous Airboat.

To collect the radiation readings during the boat's survey a Canberra UltraRadiac^{TM}-Plus Personal Radiation Monitor was added to the vehicle. The UltraRadiac^{TM} is a small, rugged, and lightweight sensor that many first responders use when responding to a radiological disaster. The UltraRadiac^{TM} is capable of sensing gamma radiation by employing a windowless Geiger-Muller tube in a range from .0001 micro Gy/hr to 350 cCy/hr with an accuracy of plus or minus 15%. With a weight of only 8.9 ounces (.56 lbs) and dimensions of 10 x 6.6 x 3.1 cm (H x W x D), the UltraRadiac^{TM} was the best candidate for the data collection sensor. The UltraRadiac^{TM} has no internal memory and so is unable to store data locally. It does have an internal infrared port in which the collected data can be transferred to another device in real time. To account for this, a Netbook with a USB infrared reader was added to read and store all the radiation data that was collected. The output from the UltraRadiac^{TM} is transmitted in a raw text format. A Python script collects data from the infrared port using the pyserial Python module to read the port approximately once per second. Data is parsed to extract the current exposure rate and logged along with system time. This log is then concatenated with the position logs from the Lutra 1.1 using synchronized system time stamps to match exposure rate to its respective GPS position.

The Lutra 1.1 comes equipped with two transportation modes: 1) tele-operation mode and 2) autonomous mode. The tele-operation mode allows the user to send a thrust and a heading to the boat. The autonomous mode supports three operation modes: 1) point, 2) path, and 3) area. Point

mode allows the user to select a point on the map in the user interface and the boat will traverse to that point. Path mode allows the user to select a series of points in the user interface that the boat will traverse to in order. Area allows the user to select the boundary points of a convex or concave polygon in the user interface in which the USV will autonomously search the area inside the polygon via a lawnmower path plan. Since the approach taken in this paper is to allow the user of the USV to tele-operate and mark each intended boundary point, the open source software for the Lutra 1.1 operator interface had to be changed. The "New B.P." button was added to allow this functionality. This new button writes the boat's current position to memory so that the current location can become a new boundary point to the user defined convex polygon. During boundary point marking, the operator can use either the tele-operation mode to traverse to the next intended boundary point or use point mode to traverse to the next boundary point. Once at the location of interest, the user then clicks the "New B.P." button to write the location to memory. The last modification made to the operator interface source code was the implementation of a customized log file. The log file created upon connection to the boat writes timestamp, latitude, and longitude to a file. As mentioned earlier, this log file can then be concatenated with the log file created from the onboard UltraRadiac^{TM} payload.

B. Path Planning Module

As stated above, the Lutra 1.1 comes with the ability to autonomously search an area inside a user defined convex polygon via a lawnmower path. For the purposes of this project, a lawnmower path will not guarantee radiation readings are taken along a line parallel to the convex polygon's edges. Therefore, a new path planning algorithm was implemented so a spiral-like path is taken. A spiral-like path reduces the need for the USV to complete multiple 180 degree turns that the USV would have to make if a lawnmower path was executed. The idea is that the original polygon that is created by the operator, as described above, forms the outer loop of the spiral and is added to a new list of points forming a new polygon. To create the next inner loop of the path, each previous boundary point from the newly created polygon is moved a fixed, user defined distance d towards the centroid of the polygon forming a new potential location. Before being added to the final path, the distance from this new location to the centroid of the polygon is calculated. If this distance is less than d, it is not added to the path, otherwise the location is added to the list of points to traverse. After each of the locations of the polygon has been adjusted and checked against the centroid, the old polygon is deleted and the newly created locations are used to form the next, new polygon. This process is repeated until the polygon is decreased to a line, i.e. two points. Once two points remain, the process is terminated and the centroid of the original polygon is added to the path to insure complete coverage of the user defined area. Upon completion of the final path, the list of coordinates generated is sent to the

boat instead of the lawnmower path the software would have generated otherwise. With this said, no hardware or software was modified on the USV's onboard system.

C. Interpolation and Visual Heatmap

The visual heatmap system has three main components: 1) communication, 2) interpolation, and 3) Google Earth overlay. Each of the components can be used independently or together in a sequence to provide the mission specialist with a visual heat map. The communication module is used to provide real-time data transmission through Java Sockets. The interpolation module is written as a Python script with four main interpolation algorithms as functions: 1) simple kriging, 2) ordinary kriging, 3) radial basis function, and 4) inverse distance weighting. Google Earth is used to overlay the heatmap from the interpolator on a geographical region. For the purposes of this paper, the real-time data transmission was not used. Instead, all data was collected then analyzed post survey.

As soon as the data collection has been terminated, the log file generated on the control end containing timestamp and GPS location is joined with the log file generated by the onboard UltraRadiac^{TM} payload containing timestamps and radiation readings. A Python script is used to accomplish this task and outputs a .csv file with each line of the file having the form "latitude, longitude, radiation reading". Next the data are passed to one of the four interpolation algorithms which in turn, creates a .png of the heatmap. Once the heatmap has been created it is then overlayed on the geographical region within Google Earth.

IV. DEMONSTRATION

The full scale test of the described USV radiation localization system took place on May 12, 2015, at one of the ponds at Texas A&M Engineering Extension Service's (TEEX) Disaster City® in College Station, Texas. Disaster City® is a 100-acre training facility that features collapsed buildings, rubble piles, derailed trains, and many other simulated disaster scenarios. For the purposes of this field test, a cesium-137 radiological source was placed on the southeast bank approximately 2 meters from the water's edge (see Figure 2) and 72 meters from where the USV was deployed. As this was an initial test, the distance was relatively short and the USV stayed in line of sight. The radiological source was transported to Disaster City® by Texas A&M's Environmental Health and Safety's radiological safety unit, meeting all the regulations and requirements imposed by the United States and the State of Texas's governments.

Fig. 2: The yellow star indicates where the cesium-137 source was placed and the blue circle indicates where the USV was deployed.

Fig. 3: The complete data collection process.

V. RESULTS

The intent of this demo was to demonstrate and test each of the major modules of the USV system. For the complete system to be successful, the following four modules had to be completed:

1) Specification of safe navigation polygon via teloperation
2) Path generation and execution
3) Radiological data collection
4) Generation of interpolation and visual heat map

The process of completing the above modules begins with the Lutra 1.1 safely navigating to each of the user defined boundary points, via tele-operation, and saving these boundary points to memory. The boundary points are saved to the same laptop that is acting as the operator control unit (OCU). Once the boundary point marking phase is complete, the resulting polygon is then passed to the getPath() function. After the getPath() function generates a list of GPS coordinates that the USV is to traverse, these coordinates are sent to the USV in the water. Upon receiving the generated path from the controller, the Lutra 1.1 then autonomously traverses to each of the desired coordinates while simultaneously collecting radiation readings. The operator is notified that the path execution is complete when the fan on the USV turns off and the path in the Operator Interface disappears. After the survey has been completed and the USV is safely out of the water, the data from the onboard UltraRadiac™ payload is transported to the OCU laptop via a USB flashdrive, and is then joined with the GPS log file created by the OCU with the common key being timestamp. This process is completed by a Python script that outputs a .csv. This .csv is then transferred to a data analysis laptop where the interpolation and heat map creation takes place. The complete process can be seen in Figure 3.
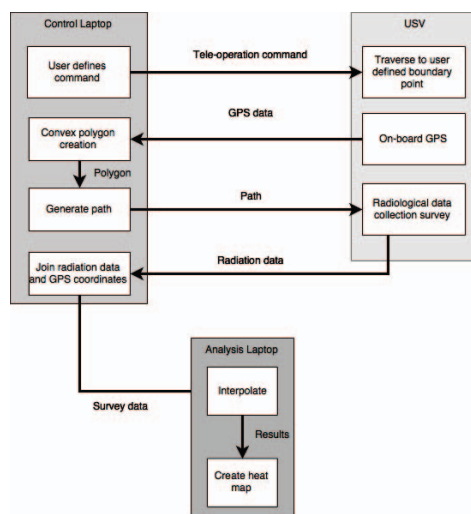
The weather conditions for College Station on May 12, 2015 were overcast with scattered showers. Due to these unfavorable weather conditions, only one trial was executed. The trial lasted 18 minutes and 19 seconds.

A. Polygon via teleoperation

The user defined convex polygon was successfully created by marking 9 boundary points. The operator used the Lutra 1.1's point autonomous mode to traverse to each of the desired points, then clicked the "New B.P." button to mark the boundary point. The area covered by the polygon was 21.58 square meters and can be seen in Figure 5.

B. Path generation and execution

In the figure below, the generated path the USV was given is shown as it appeared in the Operator Interface (Figure 4a). The spiral path was generated in less than one second and generated 17 waypoints. The runtime of the getPath() function was calculated by logging the system time before and after the call to the getPath() function. The resulting timestamps were identical, therefore resulting in a runtime of less than one second. Notice the path planning algorithm did not fully complete its execution. This software error has since been corrected and the new path plan is shown as it would appear in the Operator Interface (Figure 4b). The new path generated 26 waypoints to traverse and was generated in less than one second as well. This path was generated with the exact same boundary points as Figure 4a but has not been tested with the USV and radiation source at this time.

(a) Generated and executed path.

(b) Corrected path.

Fig. 4: Figure 4a shows the actual path plan that was sent to and executed by the USV. Figure 4b shows the correct path generation that has yet to be tested with a radiological source.

The Lutra 1.1 traversed the yellow path shown in Figure 5. The portions of the path on land are due to the fact that the Lutra 1.1 was connected to the Operator Control Unit on land, and carried by hand to and from the water. The execution of the generated path took 8 minutes and 4 seconds. This time was determined by measuring the time the motor turned on to begin the path traversal to the time the motor shut off after completing the path.

Fig. 5: The yellow portion indicates where the USV traveled. The red polygon shows the intended area formed after marking the 9 boundary points via tele-operation.

C. Radiological data collection

Once the log file created by the onboard UltraRadiac™ was transferred via a USB flashdrive to the Operator Control Unit and joined to the log file created by the OCU, a .csv file containing "latitude, longitude, radiation reading" was interpolated using the inverse distance weighting method to form the heat map shown in Figure 6. In total, 775 radiation readings were taken, with approximately .705 collected samples per second. The minimum radiation reading was 0 micro R/hr and the maximum radiation reading was 75 micro R/hr.

D. Interpolation and heat map

The heat map created in Figure 6 had an overall area of 57.61 square meters. In general, there is no set interval to determine a radiological heat map's color scheme. Color schemes are event specific based on radionuclide and exposure rate. For this demonstration the areas in green show areas that had an interpolated radiation reading between 0 micro R/hr to 39 micro R/hr. Areas in yellow show regions with an interpolated radiation reading between 40 micro R/hr to 79 micro R/hr. Though not present on this heat map, areas of orange would indicate regions with interpolated radiation readings between 80 micro R/hr to 119 micro R/hr and areas of red would indicated regions with interpolated radiation readings greater than or equal to 120 micro R/hr.
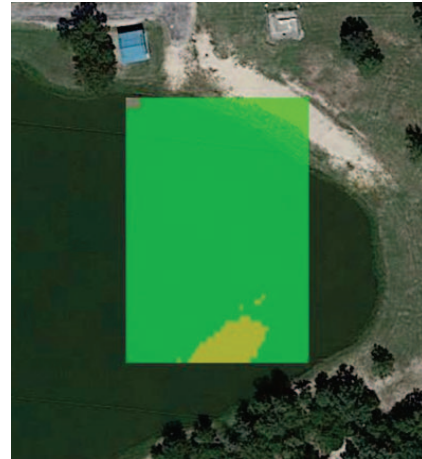

Fig. 6: The green area shows areas that had interpolated radiation readings between 0 to 39 micro R/hr and the yellow area shows regions with interpolated radiation readings between 40 to 79 micro R/hr.

E. Discussion and Future Work

The system described in this paper was successful in completing each of the four intended modules. Proof of this is in the fact that the operators of this system were easily able to produce a radiological heat map, on site, that could be given to first responders and power plant inspectors. The first benefit to this system is the ease at which the data was collected. For example, the operator of this system does not have to be an experienced operator as with some unmanned ground vehicles (UGV) or unmanned aerial vehicles (UAV). Using the Lutra 1.1's built in point autonomous mode, the operator only has to specify a safe location on the OCU for the USV to traverse to during the boundary marking phase and click the "New B.P." button to save the boundary point. After the boundary point marking phase is complete and the generated corresponding path is sent to the USV, the operator no longer has to control the vehicle. The next benefit of this system is the small size of the platform. Being man-packable allows operators to collect data in areas which a large USV could not be used. Lastly, this system allows data to be collected and a heat map produced quickly in areas that could only be collected by a marine vehicle.

The complete USV system implemented in this paper, although successful in its given task, does not come without its limitations. The Lutra 1.1 handles well in stagnant water such as a cooling pond, but would not handle as well in swift moving water such as a river following heavy rainfall. With this said, this does not mean that a better suited vehicle with a skinnier hull and more powerful propulsion system could not be equipped with a radiological sensing payload. As with fixed wing UAV's, the USV would handle better if it were to travel with and against the current in a raster-scan fashioned path plan. A combination of sensors and algorithms would need to be implemented to determine the current's direction so that this raster scan path could be generated successfully.

Future work, given the lessons learned from this system, falls into four categories. More work is needed to evaluate the navigational and sampling algorithms. As stated earlier, unfortunate weather conditions on May 12, 2015, led to only one successful trial. When conducting future trials, it will be interesting to see how varying the spacing between each loop of the spiral affects the resulting heat map. Next, the operator of the USV could have marked boundary points closer to the south east bank of the pond. Since the Lutra 1.1 currently is not equipped with a camera for a live video feed, the operator was navigating purely off of line-of-site. With the addition of a live video stream, the telo-operation of boundary point marking could be improved. Another line of investigation is to explore how real time data analysis could assist with the initial localization problem. Knowing where radiation is present would allow the planner to dynamically adapt and focus on a smaller, specific area. To accomplish this, the onboard UltraRadiac^{TM} must be modified so that data is sent back to the OCU and overlaid onto a Google Earth image of the area. Next, preliminary research has shown the UltraRadiac^{TM} requires a latency period for the sensor to collect and read the most accurate radiation level. Further investigation is needed to determine what this latency period is. Once this time is determined, station keeping can be implemented on the Lutra 1.1 so that the USV's position can be held allowing for the accurate reading to be logged. An algorithm will need to be devised so that a radiation reading is logged only when the USV has held it's position for the given amount of time. A fourth topic for future work is the addition of sediment sampling, where the USV can collect and store bottom sediment which may contain heavier radioactive particles from run off.

VI. CONCLUSIONS

This paper presented the implementation and first documented use of a micro unmanned surface vehicle (USV) for radiation localization and forensics. A Lutra Airboat 1.1 was equipped with an UltraRadiac^{TM}-Plus Personal Radiation Monitor and was used to collect radiation readings from a cesium-137 radiological source at one of the ponds at Texas A&M Engineering Extension Service's (TEEX) Disaster City® in College Station, Texas. The operator of the USV created a convex polygon to be surveyed by tele-operating the USV to each of the desired boundary points. Once the

boundary marking was complete, a spiral like path was generated and sent to the USV to autonomously traverse. The resulting radiation readings collected by the USV's onboard UltraRadiac^{TM} were used to create a visual heatmap that showed areas where no radiation was present and where radiation levels were present. A heat map, like the one produced and presented in this paper, could be given to first responders performing a search and rescue operation where radiological material may be present. The same heatmap could also be given to treaty verification inspectors trying to determine if a facility is in fact dismantling weapons of mass destruction. This platform offers operators the ability to collect radiation readings in shallow, littoral waters, areas that until now, had been unable to be surveyed.

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