DEFINITION OF A RANDOM SEARCH STRATEGY FOR SURF ZONE RECONNAISSANCE VEHICLES

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Abstract

The U.S. Navy is currently developing bottom-crawling autonomous vehicles for conducting reconnaissance in mined Surf Zone (SZ) waters (0-10 feet in depth). Regardless of whether the crawlers are used individually or in groups, the search strategy they employ to cover the assigned area has a major impact on the time it takes to complete the reconnaissance mission. Directed or pattern search strategies will ideally yield the lowest recon mission times; however, certain conditions may exist which favor the use of random search strategies. For groups of crawlers conducting reconnaissance in a SZ lane, defining a random search pattern's parameters — such as straight-run leg length distribution, random heading change distribution, initial positional distribution, search zone partition requirements, boundary turn-angle distributions, and obstacle avoidance maneuvers — is a major system specification issue. This paper presents the results of a brief simulation assessment of the effects of one of these random search pattern parameters, leg length distribution, on the reconnaissance mission time.

The assessment was performed using the Monte Carlo version of the Coastal Systems Station's Autonomous Littoral Warfare Systems Evaluator (ALWSE-MC). To focus on search parameter effects, attention was restricted to a single crawler performing reconnaissance in uncluttered, 50-yd-wide lanes in 50-, 200-, and 1,000-yd lengths. The crawler was assumed to have a proximity detector with a range of 1.75 feet, and to travel at a velocity of 1 fps. Simulation data was collected using a scenario in which the search leg length was fixed for all turns in individual run-sets, but varied from 10 seconds to 100,000 seconds between run-sets. In this manner, the sensitivity of area coverage time to leg length is determined, with the objective of identifying the range of values over which randomization should occur.

Results show a fairly broad range of optimal leg length values between 1,000 and 10,000 seconds common to all lane length cases. The time-to-cover simulation data confirm that two different causes of exponential growth occur – one at very small leg length values, and one at very large leg length values. In between these extreme values, variations are relatively small. These results indicate that a modified search strategy using a relatively large, fixed leg length with randomized turns outperforms totally random search strategies. This modified random search strategy has the potential to get close to achieving the performance of a pattern search (on the order of only 50 percent greater coverage times) without the associated reliability and navigation error risks.

Introduction

Conducting mine reconnaissance in the Surf Zone waters from the VSW region at 10 fsw to the mean highwater mark presents a special challenge for the U.S. Navy. The area is obviously too shallow for divers, and while remote sensor systems (such as COBRA) can potentially cover large areas of the SZ, they can be hampered by a variety of environmental conditions which can render minefield patterns and even individual mines unobservable or undetectable. Currently, one of the

Navy's most promising options for meeting this challenge are bottom crawling autonomous vehicles equipped with mine detection and classification sensors.

The objective of a crawler conducting reconnaissance in the SZ region is to develop a map of mine-like contacts (and, if possible, man-made obstacles) over areas large enough to be tactically significant. To accomplish this objective, the crawlers can be employed individually or in groups. The types of sensors they can be equipped with range from proximity sensors based on tactile and E-field phenomenon, to stand-off sensors such as side-scan and synthetic aperture sonars [1]. Crawler effectiveness is measured by the commonly referenced measures of effectiveness for reconnaissance: *time-to-cover (recon)* the assigned area and *object detection/classification (D/C)* statistics.

Regardless of whether the crawlers are used individually or in groups, the search strategy they employ to cover the assigned area has a major impact on the time it takes to complete the reconnaissance mission. Non-adaptive search strategies (search methods which do not adapt their fundamental area coverage pattern based on sensor detections at any platform-relative location) can be classified as *random search* and *pattern search.* Pattern searches — frequently referred to as "complete" search strategies [2] because they guarantee complete coverage of the assigned area — will ideally yield lower reconnaissance times than random search strategies; however, there are certain situations, especially in the SZ, in which random search strategies may be more effective. Three major factors which can influence whether a random search will be more effective than a pattern search include: risk of crawler loss; the crawler's communications capability; and the crawler's navigation accuracy.

Crawlers, like any underwater vehicle, can be lost due to reliability failures. They can also be trapped by counter-countermeasures (CCM). Some crawlers' communications capabilities are limited to a simple post-mission link which provides a data dump after the vehicle is recovered. In these vehicles, loss of a crawler results in loss of information about the contacts it processed and the ground it covered. In a pattern search, where an individual crawler covers an assigned area, this results in total loss of data for an area. In contrast, in a random search there is a possibility that another crawler randomly covered the same area, and thus can provide the needed data. Giving crawlers the more sophisticated capability to communicate periodically during the mission can help mitigate the crawler loss problem, since they can then provide interim data up to the point they are lost, which can help the MCM staff make contingency plans (such as adding another crawler to cover the missed area). However, sophisticated crawler communications equipment not only increase the cost, weight, and power consumption of a crawler, but they are subject to frequent, severe environmental degradation in the SZ.

In a similar fashion, poor navigation accuracy in a crawler also favors random searches. Poor accuracy leads to coverage holidays and increased localization errors, a significant problem in a pattern search. However, increasing navigation accuracy also increases cost, weight, and power consumption, and negatively impacts recon coverage time (such as when the crawler requires frequent GPS updates or smaller long baseline fields for greater accuracy).

For these reasons, random search is a leading candidate for the SZ recon search strategy using bottom crawling UUVs.

When using a random search strategy, the algorithms can be defined by setting the random distribution for leg-length and course change, the type of boundary interaction, and the obstacle avoidance maneuver. The question is, "What values provide the optimal effectiveness?" This paper describes a brief simulation analysis of SZ crawler recon performance to determine the best values for one of those parameters, the random leg-length distribution.

Methodology

In this study, the random course change distribution and the boundary reflection algorithm are both fixed. The course change is defined as a random heading angle distributed uniformly over 45-120 degrees, a course change that has been used frequently in previous studies [3]. The boundary interaction is defined as a coherent, or specular, type of reflection process. We ignore obstacle avoidance definition for now by focusing on performance in a clean, uncluttered lane.

Sometimes search strategy performance is measured by calculating the time-dependent number of targets detected. However, this leads to the results being dependent on the target/obstacle laydown (distribution), and is hence not a good performance metric for this study. It has been suggested [4] that the fraction of the assigned area covered (searched-out) as a function of elapsed time is a better measure of search performance, since it is independent of the number, type, and locations of mine-like targets. Since knowledge of (ideally large) gaps in encountered minefields is desired, the time required for crawlers to report the absence of minelike targets, *when there are in fact no targets present*, is also a tactically significant measure of performance. Consequently, area coverage is an appropriate performance metric for system search strategy definition.

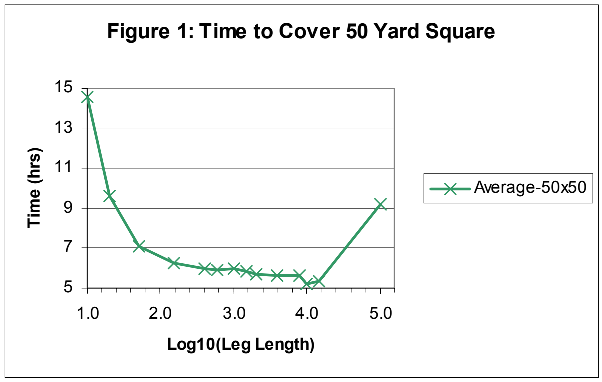
The question of leg length definition is addressed by simulating a single crawler maneuvering to cover a search area of various sizes. The simulation tool used in the study is the Autonomous Littoral Warfare Systems Evaluator (ALWSE-MC), Version 2.2.4 [5].

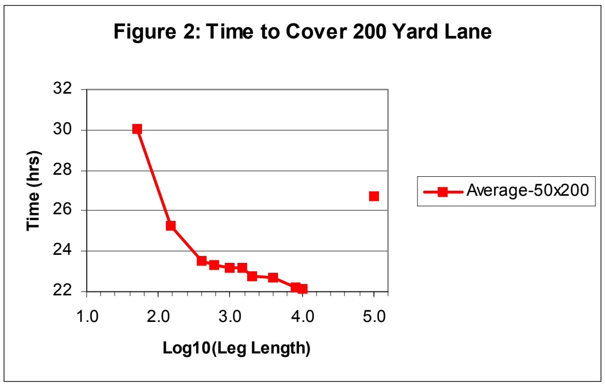
The simulation study plan is to assess the sensitivity of area coverage time to variations in a fixed-leg-length random search. The actual recommended tactical leg length is intended to be randomized within the range of optimal leg-length values observed in the fixed-leg-length simulation results.

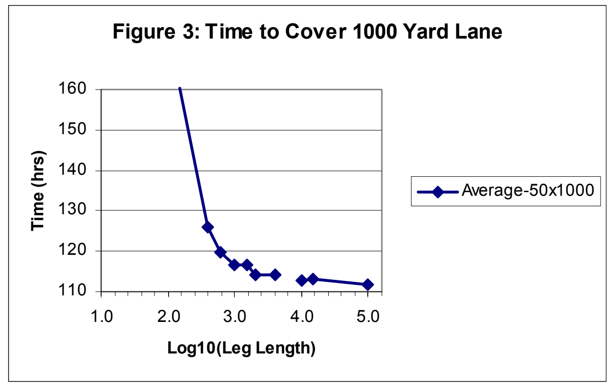
Since SZ lanes are usually 50 yd wide, we vary the lane size by changing the lane length. The lane sizes assessed are 50-by-50 yd, 50-by-200 yd, and 50-by-1,000 yd. A single crawler is initially placed at the center of the lane, and allowed to search the entire lane with a random search pattern modified for a constant leg-length and a random heading distributed uniformly over 45-120 degrees. The search radius for area coverage calculations is 1.75 feet, and the crawler speed is 1 fps.

Results

The results for average time-to-cover are shown in **Figures 1 through 3** for the 50-, 200-, and 1,000-yd lanes respectively. The time-to-cover metric is defined here for a target-free lane, and is equivalent to the time required to "swath-out" the lane to a 95% level (95% area coverage threshold). The leg lengths range from 10







seconds to 100,000 seconds, and are plotted in Figures 1-3 as $\log_{10}$ (leg length).

As expected, the average time-to-cover depends primarily on the size of the area to be searched. However, these results also indicate extremely rapid increases in coverage times for both very short leg lengths and very long leg lengths. At very short leg lengths, the random search pattern provides good local area coverage (little or no holidays), but very poor global coverage. That is, the effective speed in transiting the length of the lane is very small.

The coverage time improves as the leg length increases, but only up to a point. For very long leg lengths, the pattern of area coverage in the lane is driven by boundary reflections, since the random course changes occur only after each leg is finished. The reason for this increased time is that patterns can occur in the crawler track after some time as it begins to retrace prior tracks with redundant area coverage. While the 50-by-1,000-yd lane results don't show this long leg length phenomena, it is assumed that it exists at some leg length slightly longer than 100,000 seconds, but was simply unobserved in this study.

It is interesting to compare the minimum random search times to estimates for comparable crawlers using pattern (lawnmower) search. For a crawler with perfect navigation and track following capability, a 1.75-ft search radius implies 3.5-ft track separation. For a 50-yd-wide lane, there will be 44 tracks and 43 turns to cover the entire lane. If we assume 10 seconds per turn, then the 50-, 200-, and 1,000-yd long lanes will require 1.95, 7.45, and 32.78 hr to cover (along lane tracks). However, even modest navigation and track following errors will result in unacceptable coverage holidays of unknown size and location. Therefore, it is reasonable to require a second pass of pattern-search crawlers across the lane using offset tracks or, equivalently, use a 1.75-ft track separation on the first pass. This increases the coverage times to approximately 3.9, 14.9, and 65.5 hr, compared to approximately 5, 22, and 111 hr for the long-leg random search crawler. Note that with significant navigation and track following errors, pattern search strategies do not guarantee complete coverage and, in fact, become more and more random as errors increase.

The average times are computed from a relatively small sample size of 25 Monte Carlo runs. The standard deviation values of **Figure 4** show that over the range of leg lengths investigated, this is probably an adequate sample size, at least for trend analysis and case comparisons. The long lane shows the greatest sensitivity to leg length, with rapid growth in the time-to-cover standard deviation at both short and long leg lengths. Interestingly, the other lanes show a similar rapid growth in standard deviation for long leg lengths, but a much smaller growth at short leg lengths.

Figure 5 presents a combined view of mean and spread for time-to-cover through a plot of the average, maximum, and minimum value curves for a 50-by-50-yd lane. Here it is clear that the spread in time-to-cover values begins increasing at smaller leg lengths than the mean. It also shows that the maximum grows much faster and higher than the minimum. These observations are explained by the

Figure 4: Spread in Times to Cover - All Lanes

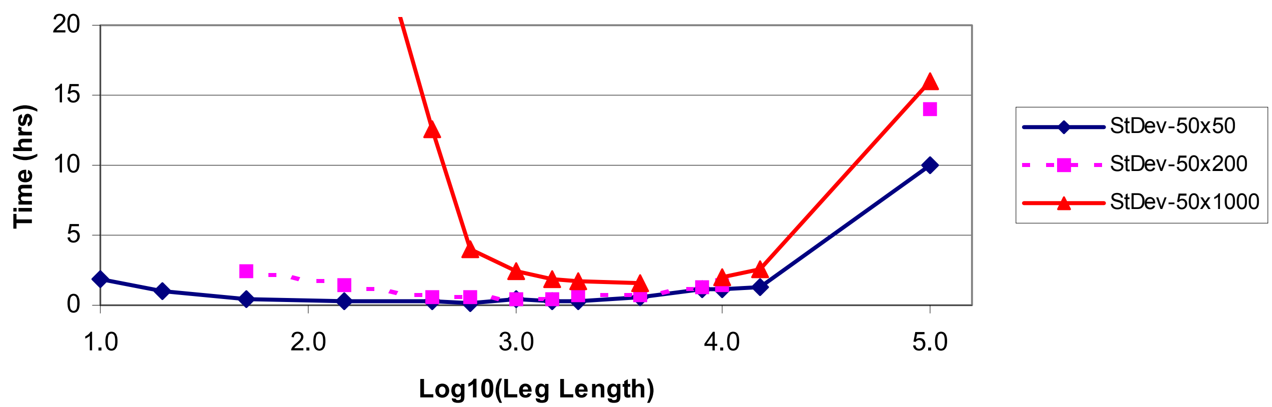
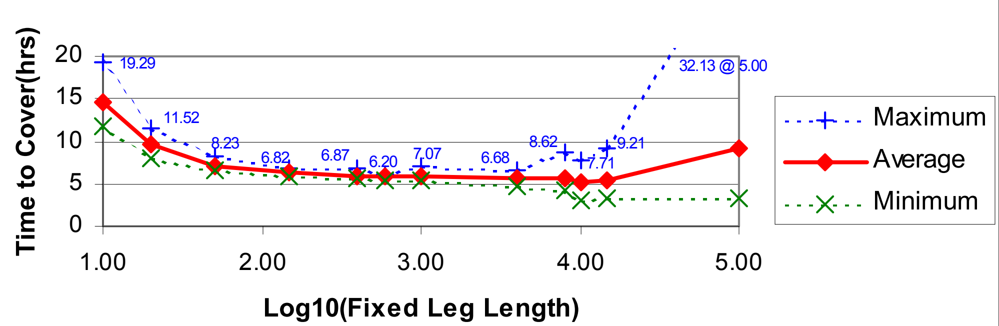


Figure 5: Sample Envelope of AC Times - 50x50



nature of the simulated crawler boundary reflection algorithm.

The ALWSE-MC simulation updates crawler positions in time steps according to the value of the variable "time-per-frame." At every step, the simulation checks the updated crawler position to see if it has reached a boundary. If so, a boundary interaction event occurs; if the boundary interaction type is "reflection," then a specular type of boundary reflection is ordered. If this specular reflection is perfect, then crawler tracks will always be re-traced after a certain number of reflections — a function of the initial boundary incident angle, the leg-length, and the rectangular search area dimensions. Because of the discrete position updates in ALWSE-MC, a crawler will actually go past each boundary some distance before a reflection is ordered. The amount of overrun is a function of the initial crawler position within the search area, the crawler velocity, and the boundary angle of incidence. The practical effect of this characteristic is that the search area boundaries are fuzzy. When successive boundary reflections occur at the same distance from the true boundary, then redundant tracks (track overlap) can occur.

Since redundant crawler tracks equates to increased elapsed time without increased area coverage, increasing leg-lengths will eventually cause increasing area coverage times. With perfect specular reflection at boundaries, one might expect to see a gradual increase in area coverage times as leg-length increases. With fuzzy boundaries, not all crawler position and incident angle combinations result in track overlap. For a large leg-length value, if any given run experiences several successive crawler legs with conditions that allow redundant crawler tracks, then the elapsed time can grow steadily with little — or only incremental — increase in area coverage.

The area coverage times for 25 runs of one scenario are shown in the scatter plot of **Figure 6**. The four extreme outliers are immediately obvious. However, one should also note the three runs with smaller amounts of track redundancy, which yield the three lesser outliers at 8-9 hr. Consequently, the rapid growth in the time-to-cover statistics with large leg length (as shown in Figure 5) is due mainly to outliers. In fact, if we omit the outliers and re-plot the statistics, as shown in **Figure 7**, we see a continuation of the earlier leg-length dependence.

The ALWSE-MC simulation screen capture images presented in **Figures 8 and 9** illustrate geometric patterns in a crawler's track for a run that produced an extreme coverage time outlier in the scenario of Figure 6. (NOTE: In these figures, the spider-web effects on the tracks reflect a screen graphics anomaly, and thus should be ignored.) In this case, two successive, redundant tracks cause the 32+ hr coverage time.

Another question which can be answered by analyzing this data is, "When does the lane coverage time scale simply by the area of the lane searched?" **Figure 10** shows a plot of the average times-to-cover and the area-scaled times-to-cover. For the scenario investigated, the average times appear to scale by area search especially well in the 1,000- to 10,000- sec interval.

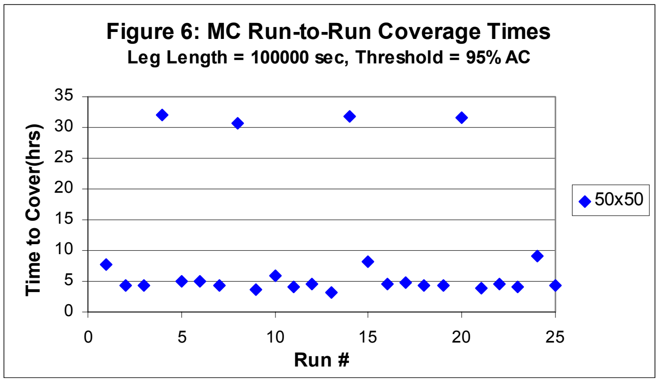


Figure 6: MC Run-to-Run Coverage Times

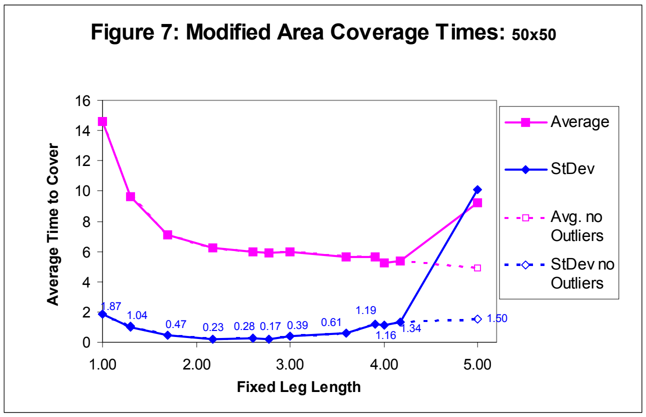


Figure 7: Modified Area Coverage Times: 50x50

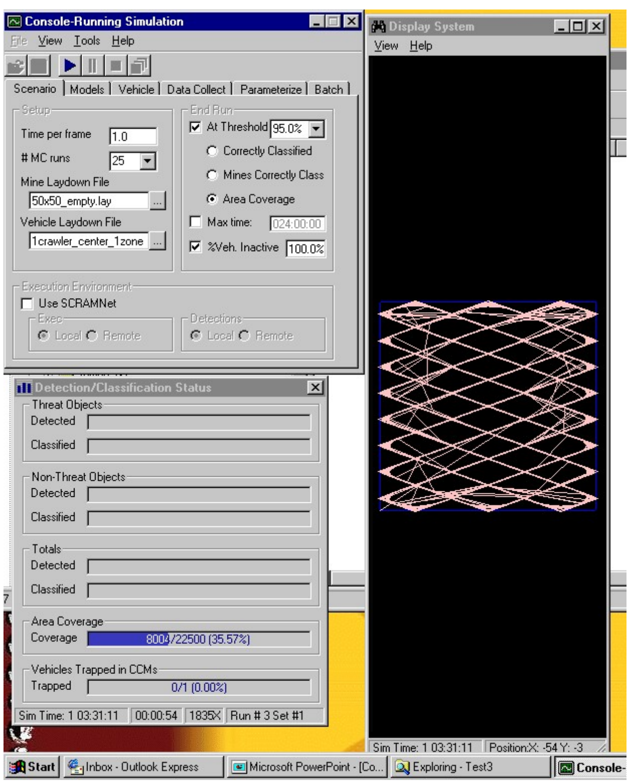


Figure 8: Screen Capture Example After First Redundant Leg

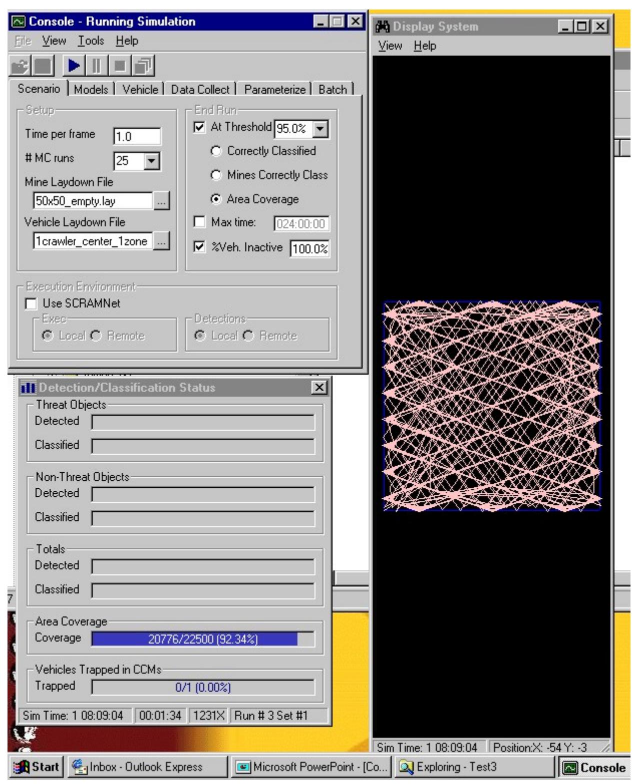
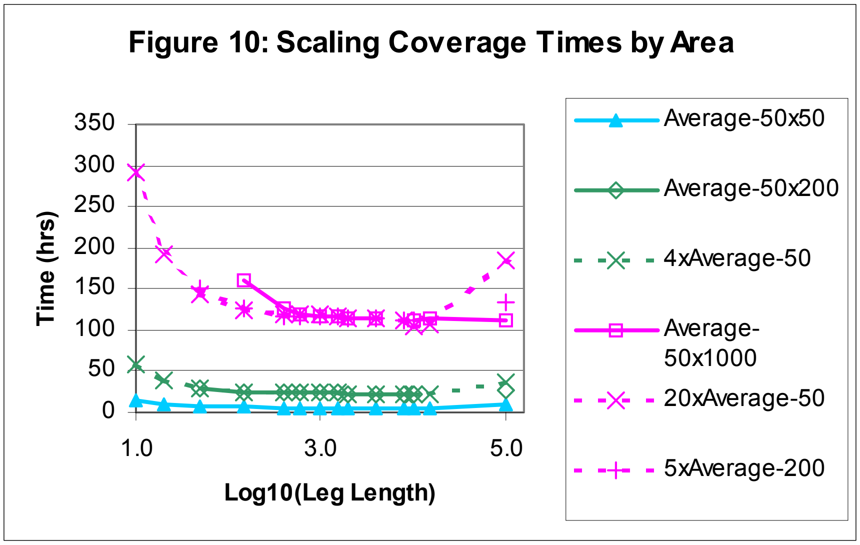


Figure 9: Screen Capture Example After Second Consecutive Redundant Leg



Conclusions

Based on this brief simulation study, the following observations can be made:

- For the tactically significant search areas (lanes) of interest, the random leg lengths should be more than about 600 seconds long, and less than about 10,000 seconds long.
- For random headings between 45° and 120°, there does not appear to be any motivation to randomize the leg length.
- For the scenario and lane sizes studied, a leg length of 8,000 seconds is approximately optimal (minimum mean and standard deviation), independent of lane length.

These data suggest that there is potential for defining a slightly better "random" search tactic. If leg length is infinite (i.e., not randomized), then the area coverage time will be minimized. (The exception is outlier cases (redundant search tracks), which will occur with greater and greater frequency as leg length increases.) If we employ a modified specular boundary reflection, wherein we intentionally dither the specular reflection angle (heading), then we should avoid long redundant tracks and the associated outlier events. Consequently, the resulting time-to-cover curves may appear close to the dashed mean curve in Figure 7. While the standard deviation in Figure 7 does not indicate a global minimum would be approached as leg-length tends toward infinity, it is unclear what the effect of removing all outliers at all leg-lengths would have on the high leg-length behavior of the time-to-cover standard deviation. It should be noted that the suggested dithered boundary reflection is not equivalent to selecting a new totally random heading on boundary encounter.

This study has shown that long leg-length random search strategies employing reflection-type boundary interactions can provide area coverage that is robust to variations in the lane size (subject to area scaling). High accuracy in crawler position fixing is required only for contact localization. This is significant in SZ recon situations, where the search lane is long or when the acoustic LBL baseline-to-SZ lane separation is large. It should be possible to avoid the requirement for continuous and constant LBL coverage for recon in the SZ, and even in the VSW regime.

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Abbreviations

SZ – Surf Zone
VSW – Very Shallow Water
ALWSE-MC – Autonomous Littoral Warfare Systems Evaluator-Monte Carlo
COBRA – Coastal Battlefield Reconnaissance and Analysis
fsw – feet of sea water
MCM – Mine Countermeasures
GPS – Global Positioning System
fps – feet per second
UUV – Unmanned Underwater Vehicle
LBL – Long Base Line

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