

# CRAWLER CONTROL STRATEGIES AND THEIR INFLUENCE ON MINE FINDING CAPABILITIES

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## ABSTRACT

Autonomous underwater vehicles (AUVs) have found a permanent application doing mine countermeasures (MCM). Autonomous crawlers can be used to perform mine search patterns, but in doing so can encounter many problems, one of which is obstacles. For a crawler, knowing how to avoid obstacles and what to do after avoiding obstacles is important to performing searches quickly and effectively. A fuzzy logic controller was developed to perform a comparison between point to point control and trajectory control with mine finding capability being the basis for comparison. A random walk control method was also simulated to show how it compared to the other methods. Search times were found to be similar, but the trajectory control was found to be more reliable at finding a larger percentage of mines. The trajectory control was optimized to more closely follow the trajectory and a comparison was performed between the baseline and optimized trajectory controls. After optimization, the crawler was able to stay on a straight line path for a larger percentage of the search time. This resulted in better mine finding performance than the pre-optimization trajectory control.

## BACKGROUND

Tracked vehicles designed to move along the floor of a body of water are commonly referred to as crawlers. Crawlers have multiple uses, including camera deployment, exploration, and excavation. A typical crawler is shown in Figure 1.

The Navy is currently using crawlers for mine countermeasures (MCM). Crawlers are used to detect and classify mines in very shallow water (VSW) (20-40 ft.) and surf zone (SZ) (< 20 ft.) areas. Autonomous submarines are also being used for mine countermeasures. They can sweep large areas quicker than a crawler due to higher velocities and fewer natural obstacles. Crawlers can play a supporting role to the

submarines by reacquiring possible mines and performing a more detailed classification. Crawlers lack the speed of the submarines, but can safely move closer to and spend a longer duration at suspected mines in the SZ and VSW.



**Figure 1** – Typical crawler and rotating head sonar

Crawlers can also perform search patterns, which is most valuable in environmental conditions that make submarine use difficult. A typical search pattern is the lawnmower pattern in which evenly offset parallel sweeps are executed. Other search patterns such as an expanding square are considered less ideal for finding mines quickly, but are based on the same idea of moving between mission specific locations (referred to as waypoints).

The goal of MCM is to find all mines in a given area in the shortest time possible with no risk to human life. This is why autonomous underwater vehicles (AUVs) like crawlers and submarines are being developed. Current Navy standards want to be able to sweep a 30 by 30 mile area in 7 days. To meet this requirement it will be necessary to use a large fleet of AUVs.

Some of the greatest hurdles to MCM are the harsh conditions in the very shallow water (VSW): rock, kelp, surge current, unstable ground, low visibility, unreliable

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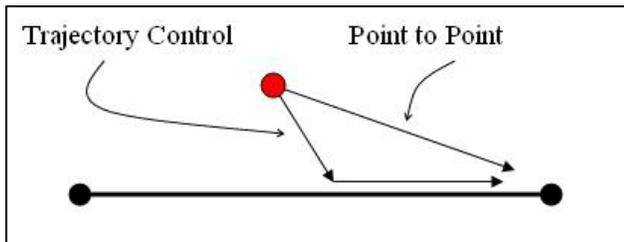
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communication, etc. [3] Obstacle avoidance is important in these conditions to ensure vehicles do not become disabled or deactivated to minimize time of search.

There are many strategies for avoiding obstacles and just as many strategies for what to do after an object is avoided. Current crawler technology is to use a forward mounted tactile sensor (bumper) to determine when an obstacle is encountered and is then avoided by a predetermined set of maneuvers. Using a rotating head sonar, shown in Figure 1, a crawler could see obstacles ahead and avoid them by finding the shortest path around. After an obstacle is avoided, the crawler can either return to the original heading or head directly toward the next point in the search pattern. Returning to the original path is referred to as trajectory control. For a crawler the trajectory is a straight line path between search pattern points. Heading directly to the next point is referred to as point to point control.



**Figure 2** – Trajectory control and point to point control. The top point is the crawler and the two bottom points make up the intended path.

## CONTROLLER

A linear, fuzzy logic controller was developed for an autonomous underwater crawler. Fuzzy logic has previously been considered for crawler control [4, 5]. The controller is hierarchical in design with obstacle avoidance, path finding, and supervisor modules. The obstacle avoidance module takes information about the nearest obstacles and outputs a recommended corrective heading. It attempts to avoid obstacles using the smallest possible deviation from the current vehicle heading, but it has no inherent path finding abilities. The path finding module takes information about the current vehicle heading and the desired vehicle path and outputs a corrective heading to attempt to stay on the path. The path finding module used without the obstacle avoidance module would make the vehicle follow a straight line between a series of predetermined point without avoiding any obstacles. The supervisor module takes the recommended heading from the other two modules and combines them to create a final heading recommendation. The fuzzy logic rules and control variables and parameters can be found in detail in [5].

The different between trajectory and point to point control in the control logic is that for trajectory control the path is defined as the straight line from the previous waypoint to the current waypoint, while for point to point control the path is a line from the crawler's current position to the current waypoint.

## SIMULATIONS

The software used for the simulation environment is the Autonomous Littoral Warfare Systems Evaluator – Monte Carlo (ALWSE-MC) developed and maintained by Naval Surface Warfare Center Panama City. ALWSE-MC simulates autonomous vehicles performing mine reconnaissance/mapping, clearance, and surveillance in a littoral region. It uses Monte Carlo methods to assess performance and predict performance parameters [5].

The fuzzy logic controller is written in an ALWSE-MC behavioral module. During each iteration of a simulation run, ALWSE-MC calls the behavior module and uses the outputs of the fuzzy logic controller to move the vehicle. Assumptions made in this model are  $\pm 3^\circ$  heading bias error,  $\pm 3^\circ$  heading random error,  $\pm 3\%$  speed bias error,  $\pm 3\%$  speed random error. Location updates are given to the vehicle every 90 seconds with a 90% success rate.

Three simulations were performed; one each for trajectory control, point to point control, and random walk. Each simulation consisted of 100 runs in a 200 meter by 200 meter minefield filled with 20 mines. Each run consisted of different randomly located mines and 200 randomly placed obstacles of 2 meters in diameter. Simulations runs using trajectory and point to point control were ended when the crawler finished one complete pass through a lawnmower search pattern. Random walk runs were terminated at the mean time of completion of the trajectory and point to point control searches. This was done to make a more meaningful comparison between the three strategies.

The sensor used for mine detection was a simulated side scan sonar. The sensor is one built into ALWSE-MC and has a probability curve that may or may not represent the capabilities of actual side scan sonar. The probability curve shows the probability that the sonar can detect a mine at a given range and can be seen in Figure 3.



**Figure 3** – Side scan sonar probability curve. Range is in meters.

A stochastic optimization procedure was developed using ALWSE-MC simulations and a simplex method routine to help further improve the fuzzy logic using trajectory control. The optimization procedure was an iterative process in which a set of 25 simulation runs were performed, the average performance function was calculated, a simplex calculation was executed, and a new set of fuzzy logic parameters were recommended. This process repeated until a termination criterion based on the difference of means of the performance function was met. The performance index is found in equation 1.

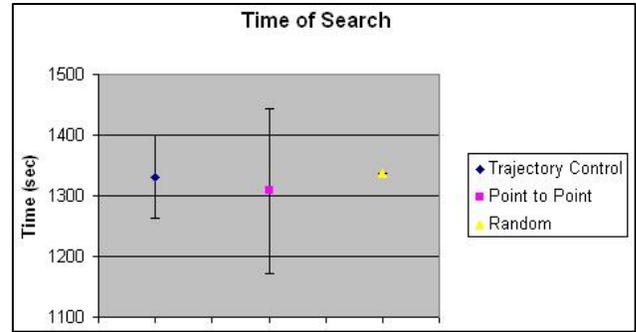
$$PI = Avg\_dev + 1000 * Collisions \quad (1)$$

Crawler performance (PI) was quantified using a performance function designed to penalize a crawler for colliding with obstacles (Collisions) and deviating from a straight line path. Deviation from straight line path (Avg\_dev) was used as a criterion to teach the vehicle to perform trajectory control better by staying closer to the trajectory while avoiding obstacles.

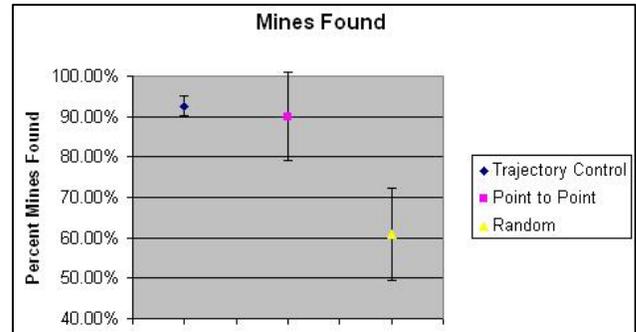
The terminating criterion for the optimization is based on the difference of means of the performance index. This was chosen because the objective parameter, the performance index, is stochastic. From observation of optimization convergence for similar systems, it was decided that the optimization would be terminated when the difference of means of the performance index using a 90% confidence interval included zero for three consecutive iterations.

## RESULTS

There is no statistical evidence that there is a difference in time of search between the trajectory control and the point to point control, see Figure 4. The random walk time of search was made to match the mean of the trajectory control time of search and was used as the termination condition for the random runs. This allows the random walk to be compared to the other two strategies in mine finding capability as seen in Figure 5.

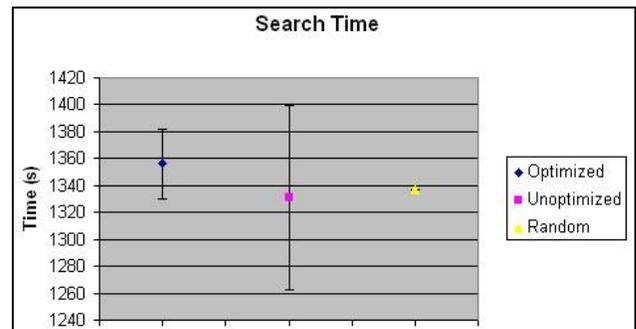


**Figure 4** – Time of Search



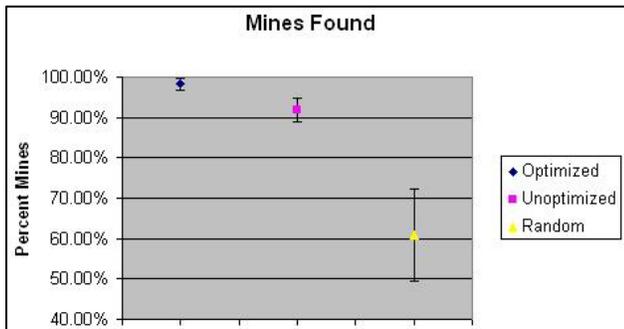
**Figure 5** – Mines Found

Both point to point and trajectory control outperformed the random walk in finding mines. Observation of the random runs found that given the time of search, the crawler would typically not be able to get to all the corners of the search area, leaving a number of mines unfound. The error bars represent one standard deviation. There is not a statistical difference in the mean number of mines found over the 100 runs for the point to point and trajectory controls. However, the point to point control could tend to leave gaps in the pattern and miss mines.



**Figure 6** – Search time before and after optimization

After optimization the trajectory control search time became more consistent as the total distance traveled by the crawler became closer to the distance of the lawnmower search, see Figure 6.



**Figure 7** – Mines found before and after optimization

The mine finding capability of the lawnmower search pattern increased after optimization from about 92%  $\pm$  2% to about 98%  $\pm$  1% (Figure 7). This is believed to be because of less gaps in the search since the optimized controller returns to the path quicker than the unoptimized controller.

## CONCLUSIONS

Trajectory control and point to point control have the capability of performing equally well, but trajectory control has shown to have less variance and is therefore a better choice for MCM missions. The closer a crawler can stay to the lawnmower pattern while avoiding obstacles, the better its mine finding performance. Total search time was expected to be lower using a point to point control, but it was found that there was no difference.

To reach the desired Navy goal of sweeping a 30 by 30 mile area in a week by using trajectory control, there would need to be well over 100 vehicles (126 assuming a 22 minute time of search). This is the motivation for future work in determining fleet control strategies and communication languages.

Random walk control did not perform as well as the other two methods, but it should not be discredited as a viable option. Random walk can be performed using less communication bandwidth and may take less processing capability.

The side scan sonar model used to detect mines was not based on an actual sensor. Differences in the results would be expected if a different sensor model was used. Depending on the sensor, time of search and mines found would be different. A longer range sensor would increase lane widths and decrease time of search.

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