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Coverage Algorithms for an Under-actuated Car-Like Vehicle in an Uncertain Environment

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***Abstract*— A coverage algorithm is an algorithm that deploys a strategy as to how to cover all points in terms of a given area using some set of sensors. In the past decades a lot of research has gone into development of coverage algorithms. Initially, the focus was coverage of structured and semi-structured indoor areas, but with time and development of better sensors and introduction of GPS, the focus has turned to outdoor coverage. Due to the unstructured nature of an outdoor environment, covering an outdoor area with all its obstacles and simultaneously performing reliable localization is a difficult task. In this paper, two path planning algorithms suitable for solving outdoor coverage tasks are introduced. The algorithms take into account the kinematic constraints of an under-actuated car-like vehicle, minimize trajectory curvatures, and dynamically avoid detected obstacles in the vicinity, all in real-time. We demonstrate the performance of the coverage algorithm in the field by achieving 95% coverage using an autonomous tractor mower without the aid of any absolute localization system or constraints on the physical boundaries of the area.**

***Index Terms*— Ground robots, coverage algorithms, path planning.**

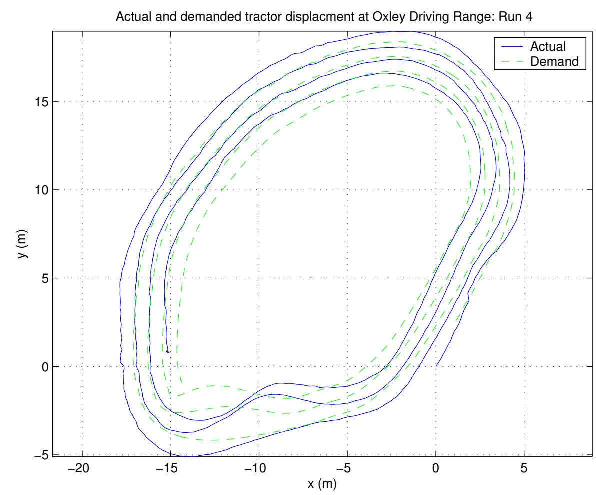


Fig. 1. A real example of a simple inward spiral. Note that the tractor could not achieve the demanded rate of turn in the bottom left-hand corner of the figure.

I. Introduction

Many applications of mobile robots require the use of *coverage algorithms*. Applications such as autonomous lawn mowing, ice rink maintenance, vacuum cleaning, de-mining and some agricultural and mining tasks all require a mobile robot to move over an area of ground and to cover that area completely. Ideally, the mobile robot should cover the area in the most efficient possible way, saving energy and time.

Coverage algorithms have been a popular research topic over the past two decades. Several approaches have been suggested based on mathematical models [1], [2], [3], those that take uncertainty into account [4], [5] and even Neural Network based techniques ([6]).

There are many different types of basic path patterns proposed for coverage algorithms, the most common being parallel swath or zig-zag patterns. Other typical patterns include inward and outward spirals, random walks and wall following. A common technique for dealing with obstacles in the environment is to decompose the area into unobstructed cells [7], [8] and then cover each individual cell independently. The disadvantage of this approach is the requirement of an a priori map of the environment and the decomposed cells may be too small for under-actuated vehicles to move around in.

Other limitations to existing coverage algorithms are their need for absolute localization (i.e. use of GPS outdoors), not taking robot kinematics into account or requiring extensive manual training for various environments. It is a challenge to develop a system that can handle any coverage tasks in indoor or outdoor environments with various robotic platforms with different kinematic constraints.

A. Our Previous Work

In previous work [9], we described our first attempts at autonomous coverage of large outdoor areas for a lawn mowing task. Here, a human driver first drove a small tractor (a ride-on lawn mower) around the perimeter of the area to be mowed, while the system recorded its position using GPS. A simple inward spiral algorithm was then used to pre-compute a trajectory to cover the mowing area. The tractor then autonomously navigated along the spiral trajectory while cutting the grass. Like [10] we used high-quality RTK-GPS for localization.

The tractor, like many real-world mobile robots, is an under-actuated car-like vehicle. This means that it has a limited turning radius and turning rate. Fig. 1 highlights this issue. The figure was created from an autonomous mowing experiment using our tractor at a golf course and shows the planned path and the actual trajectory of the vehicle during one of the trial runs. As can be seen in the bottom left corner of the Figure the actual trajectory of the vehicle deviates form the planned path. This is due to the limited turning rate and turning radius of the vehicle.

More recently, we have begun to address the coverage problem and the issue of reliable vehicle localization. Unfortunately, the state-of-the-art in outdoor coverage is to use high-precision GPS based localization, which is not suitable for precise operations near trees and other obstructions.

In [11] we describe a system architecture that integrates laser-based localization and mapping using the *Atlas Framework* [12] with *Rapidly-Exploring Random Trees* (RRT) [13] local path planning and *Virtual Force Field* [14] obstacle avoidance. We also demonstrate the performance of the system in simulation and with real world experiments.

This paper describes a set of global path planning algorithms, when used together, prove suitable for outdoor coverage tasks. The algorithms take the kinematic limitations of the vehicle into account and generate smooth paths while dynamically avoiding obstacles.

B. Paper Outline

The remainder of this paper is structured as follows. Section II describes the *Global Path Planners*. Section III shows results from our tests running on the tractor in different outdoor environments. In Section IV we conclude on our experiments and propose further work.

II. Path Planning for Coverage Tasks

Earlier work [9], [15] has shown that the inward spiral algorithm is appropriate for area coverage. The authors in [4] argue that, path planning algorithm efficiency can be measured by the number of turns the generated paths contain, due to the need of deceleration and acceleration in turns. It is also known that turns produce wheel slippage which compromises the odometry accuracy. A spiral path contains at most 90° turns, compared to 180° turns in parallel swath and zigzag paths. Thus, spiral paths can be carried out with higher velocity without introducing additional wheel slippage. Another advantage of the spiral motion is that, the robot will be passing through the local environment from the same direction and will be seeing the same landmarks from the same side, which aids localization.

Using inward spiral for motion planning is especially useful in large areas. However, due to the limited turning ability of under-actuated vehicles, the trajectory becomes infeasible as the area becomes small and narrow. Other motion planning algorithms are therefore needed in addition to the inward spiral algorithm. We suggest three global path planning algorithms producing inward spiral paths, shifting spiral paths, and greedy paths.

In our architecture, these planners use the knowledge of the environment available in the *Atlas Framework* [11] to generate global trajectory way-points. Short sequences (~ 10 m) of the global trajectories are then passed to the local path planner which uses the way-points to generate a more feasible and precise path.

A. The Coverage Task

The input to the system is the circumference of the area needing to be mowed. The input is given by driving the mower manually around the perimeter of this area. During this manual run the robot creates an initial map of the environment.

The task planner will use this map as an estimate of the robot's surroundings. The first step of the coverage is done using the *Inward Spiral* algorithm, which creates a spiral path around the area while offsetting the path inward towards the center. When the remaining area in the center is below a minimum threshold defined by the vehicle kinematics, the robot switches from *Spiral Inward* to *Spiral Shift*. Using *Spiral Shift* the inner area is covered. Depending on the size and shape of the area being covered, and the number, shape and size of the obstacles within that area, there might be holes in the coverage. These holes can be covered using a *Greedy* path planner.

B. Global Path Planners

The *Spiral Inward* path planner creates paths around the perimeter of the mowing area. For every loop, the path is offset inward towards the center of the area; hence the name *Spiral Inward*. The path is not generated beforehand but rather dynamically such that it takes the obstacles and the shape of the nearby area into consideration. The amount of offset inward depends on two parameters: the coverage tool or milling width, W, and the minimum desired amount of overlap, o_{min}. The critical point to maintain overlap is when a minimum radius turn is being performed as this is the point where the largest distance between two loops is introduced. The amount of offset is therefore set as:

$$d_{offset} = (W - o_{min}) \cdot \frac{1}{\sqrt{2}}$$

The minimum offset is zero, which results in reusing the path from the last loop.

When the path contains obstacles the planner avoids them by generating a trajectory which reuses the path from an earlier outer loop. Fig. 2 shows this scenario. However, in the case of wide obstacles this procedure is limited by the steering angle of the vehicle. In such a case the vehicle must turn before reaching the obstacle in order to make it to the outer path.

The curvature of the trajectory and the curvature variance both increase for every loop if the inner loop path is just an offset of the outer loop path. The variance can be minimized by implementing a low-pass filter on the way-point generator to smooth out high curvature trajectories. Implementing a low-pass filter has two benefits:

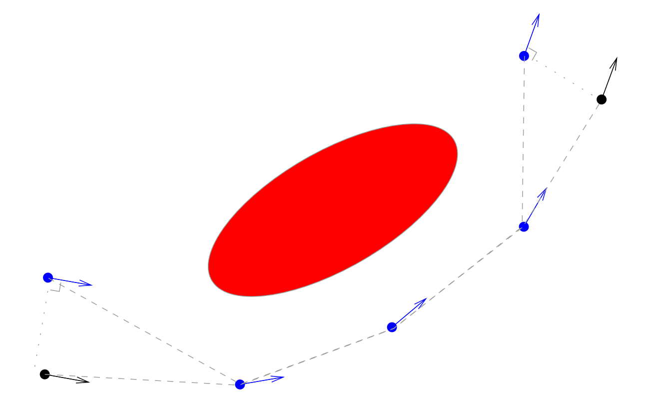


Fig. 2. The *Spiral Inward* path planner uses the information from earlier outer loops to calculate a path around obstacles. Here the blue path is obstructed and way-points from the black outer reference trajectory are used.

- Instead of increasing, the variance of the curvature of the path will decrease for every loop, thus facilitating the path following for the robot.
- Any random initial shape will eventually result in a smooth arc shape. This is desirable as it will ease the coverage of the inner area.

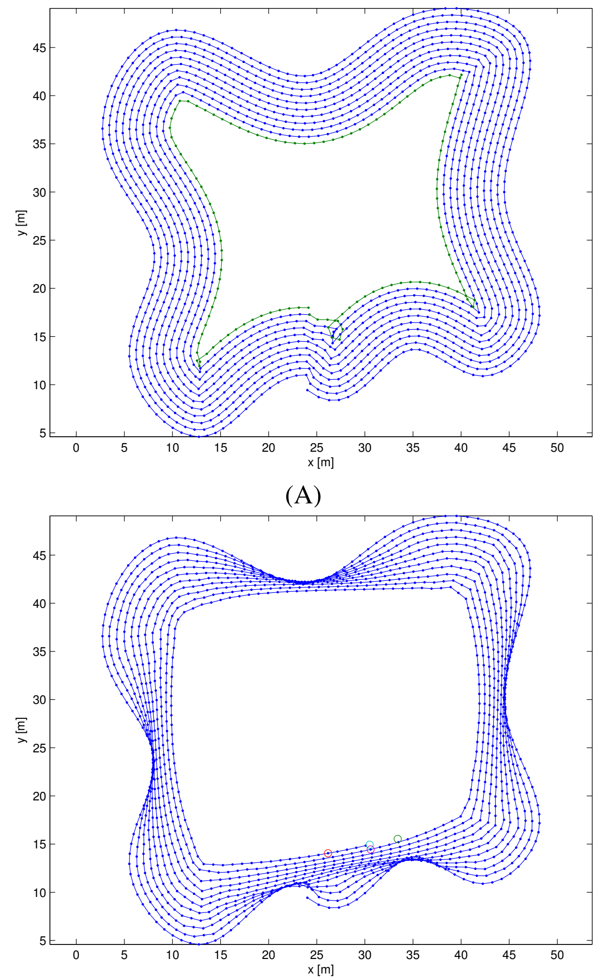
However, there is a cost in that it results in more overlap in convex areas. Fig. 3 illustrates the effect of the straightening algorithm as compared to a the purely offset spiral trajectory.

Some curves cannot be smoothed out sufficiently by the curve straightening algorithm and special treatment is necessary. This path planning algorithm also employs sharp corner detection. A sharp corner is defined as a curve with a tighter curvature than is feasible by the tractor. When a sharp corner is detected the path generated is not an filtered offset of the outer reference curve but is a shifted replica created by the measure of error from the normals to the reference points. These trajectories are produced before the curvature reaches the vehicle maximum. Fig. 4 indicates the difference between the offset path and the shifted replica of a sharp turn.

The *Spiral Shift Path Planner* is used when the inner area is small, such that it is no longer desirable or even feasible to continue using *Spiral Inward*. The *Spiral Shift* algorithm is inspired by observing the paths used during ice resurfacing. Ice resurfacing machines have similar constraints due to limited vehicle turn radius and an outer bound limit. At ice rinks the coverage problem is solved by following a shifted spiral pattern.

A shifted spiral trajectory is created by traversing loops half the width of the area being covered and shifting by the width of the vehicle after every loop. The advantages of this movement is that it avoids sharp turns, can be implemented on all vehicles, goes to the edge, and covers the entire area with limited overlapping coverage.

Mowing, however, is more difficult as obstacles must be avoided as well. Obstacles are often dealt with by subdividing the area into smaller sub-areas [7], [8], [16]. This technique breaks up the coverage task and requires a priori



(A)

(B)

Fig. 3. A large $40m \times 40m$ area with soft turns will end up having corners infeasible for the tractor to follow (A). This effect is avoided by generating a smoother straightened path (B). The effect is shown after 11 loops for both cases.

knowledge of the obstacles within the area. We have chosen to avoid obstacles by creating paths around them rather than splitting up the area as sub-areas often end up being too small to traverse with the constraints of a large car-like vehicle.

The *Spiral Shift* algorithm must be initialized before the width or height of the remaining area reaches $4 \times r_{\text{min}}$ or $2 \times r_{\text{min}}$ for the vehicle to be able to make the turns of the trajectory. The turn radius of our tractor is $r_{\text{min}} = 2.25\,\text{m}$ and Fig. 5 shows the steps of a shifted spiral path on the minimum width area of $9.0 \times 6.75\,\text{m}^2$.

While the *Spiral Inward* algorithm and the *Spiral Shift* algorithm are capable of producing feasible trajectories under the constrained circumstances, it is still common that gaps are introduced in the coverage. To complete the coverage these occasional gaps must be addressed as well. The *Greedy* algorithm is used to finish off any remaining uncovered areas. This task resembles the traveling salesman problem [17]. Compared to the traveling salesman problem we do

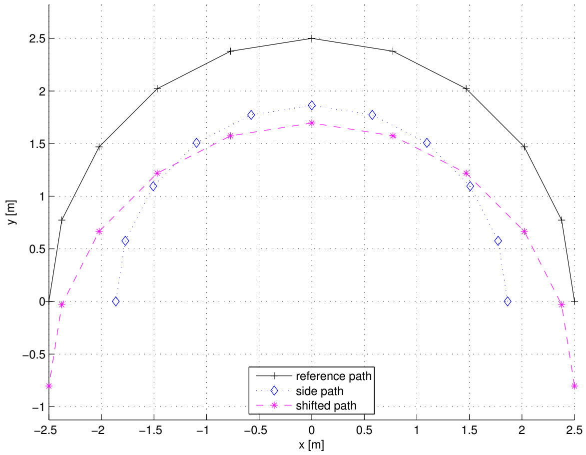


Fig. 4. Sharp corners need to be smoothed out. The effect of smoothing out the curve compared to the shifted replica of the outer curve is shown here. Reference way-point path (black crosses), normal *Spiral Inward* side way-point path (blue diamonds) and the shifted way-point path (magenta stars).

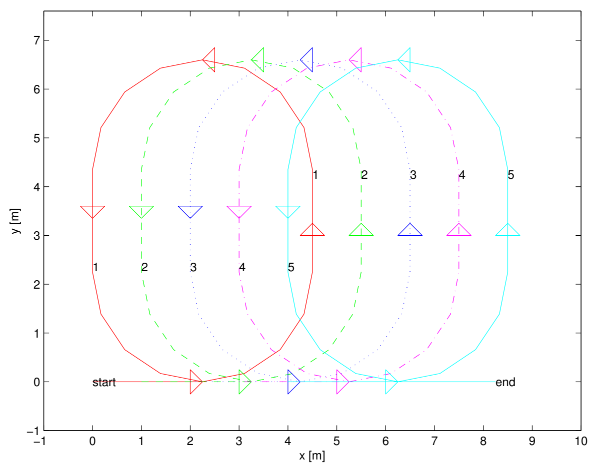


Fig. 5. The *Spiral Shift* path on a 9.0 m by 6.75 m area. With the kinematics of our robot 5 loops are needed to cover the 60 m^2. The arrows show the direction of travel.

not have the constraint of returning to an initial position but the following restrictions exist for the path planner:

- The generated paths to the uncovered areas should be as short as possible to minimize overlapped coverage.
- The vehicle kinematic limitations must be taken into consideration.
- The area has a boundary and contains obstacles which must be avoided

III. Results

A. Real World Tests

We have tested our system using the *Spiral Inward* and the *Spiral Shift* algorithms outdoors with our robotic mower. The first test site is an industrial compound with an area of approximately 30 m by 40 m containing obstacles of various sizes. The surface of this area is smooth and is made of concrete, Fig. 6. The second test site is a rough grassy

Fig. 6. Test area 1 is in industrial area of approximately $30 \times 40\ \mathrm{m}^2$.

Fig. 7. Test area 2 is an unstructured grassy area with trees and bushes.

area which is very uneven, has several smaller and larger inclinations and is occupied with lots of trees, Fig. 7.

The results of a run in the compound area and a run in the grassy area are shown in Figs 8 and 9. Fig. 8 shows how the area is covered initially using inward spiral trajectories and then using shifted spiral trajectories. A few holes are left when the coverage is done due to the obstacles and the paths generated by RRT when avoiding them.

The coverage of the grassy area shown in Fig. 9 has more holes and sharp turns. These holes are mainly introduced as a result of the robot having difficulties following the path given over a bumpy and slippery surface. Furthermore, occasional ground striking of the laser scans introduced some temporary obstacles which were avoided using RRT.

B. Performance Metrics

The quality of a coverage can be measured in different ways depending on the main priorities of the task. One important metric is the percentage of covered area and the time it has taken to cover this area. Figs. 10 and 11 show the coverage map of the tests made in the compound and on the grassy area presented above. These figures show which areas have been covered, the amount of overlap indicating redundant coverage and where the holes are in the coverage.

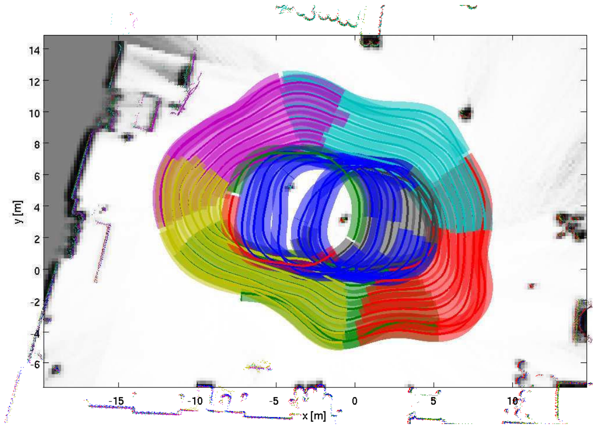


Fig. 8. Result of coverage on smooth surface with a few obstacles. The area covered is approximately $278\,\mathrm{m}^2$. Each map of the *Atlas Framework* is colored individually.

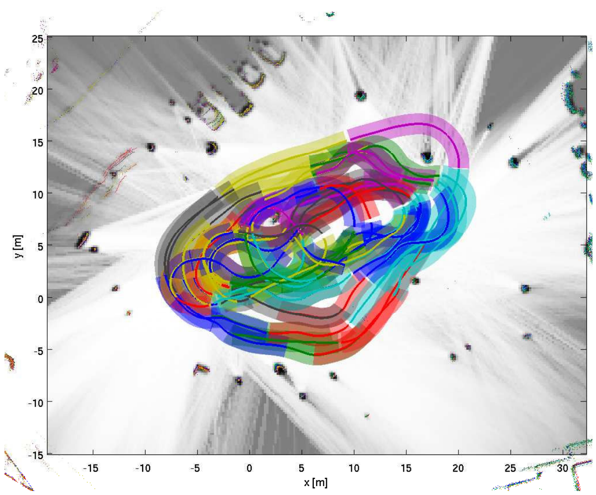


Fig. 9. Coverage result of a 321 m^2 rough inclined grassy area with several trees shown using the maps from the *Atlas Framework*. Note all the trees and bushes in and around the covered area.

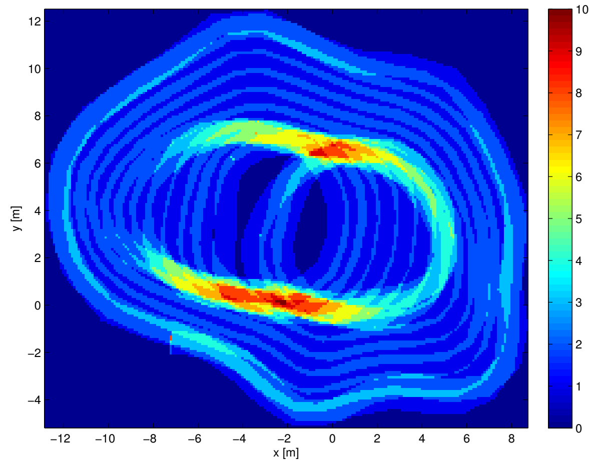


Fig. 10. The coverage map is illustrated with the number of overlaps ranging from 1-10.

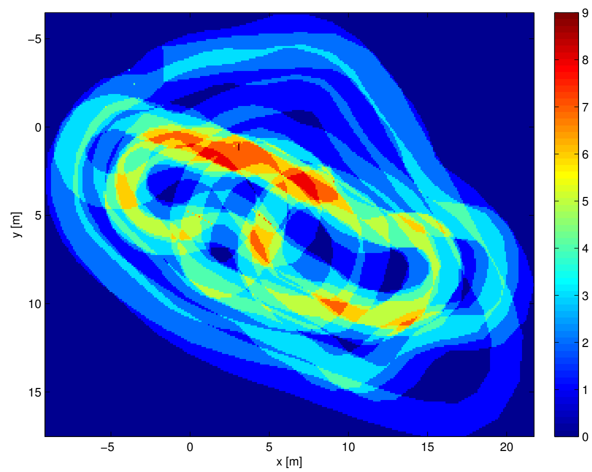


Fig. 11. The coverage map is illustrated with the number of overlaps ranging from 1-9.

Figs. 12 and 13 depict the coverage percentage. In the compound area 99% of the $278\,\mathrm{m}^2$ area was covered in $12\,\mathrm{min}$ and in the grassy area in $15\,\mathrm{min}$ more than 95% of the $321\,\mathrm{m}^2$ area was covered using *Spiral Inward* and *Spiral Shift* algorithms. From the figures it can be seen that 60-70% of the area is covered twice. This may seem big, but this is due to the amount of overlap calculated in the coverage. Due to navigation and localization uncertainties we have chosen to have an overlap of $0.15\,\mathrm{m}$ on each side, which corresponds to 30% of the covering width. These are rough measurements as they are manually estimated. Note that when covering the compound area the coverage planner used a width of one meter to resemble the use of a sweeper, whereas, on the grassy area the width was two meters to match the width of the cutter blades.

IV. Conclusion and Future Work

The limited turning ability of the tractor, the constraint of never moving backward, the shape of the area being mowed as well as the obstacles within the area all complicate the coverage task. In this paper, we have described a set of global path planning algorithms suitable for autonomous coverage tasks for under-actuated car-like robots as they address these issues. These algorithms generate trajectories with smooth turns feasible to follow while taking obstacles in the environment into consideration as well.

The planners described are named after the basic patterns they produce. The *Spiral Inward* planner generates paths suitable for covering the area near the perimeter and the *Spiral Shift* algorithm fills out the center of the covered area with a shifted spiral. The test results introduced in this paper show that using these two algorithms the robot covers more than 95% of an unknown unstructured areas autonomously. In order to achieve more complete coverage further path planning algorithms (i.e. a *Greedy* planner) will need to be integrated into the current system.

Currently an RRT path planner is used as the lower-level path planner. We have encountered difficulties controlling the produced path from this planner. To continue using this planner we will need to improve it to follow the desired way-

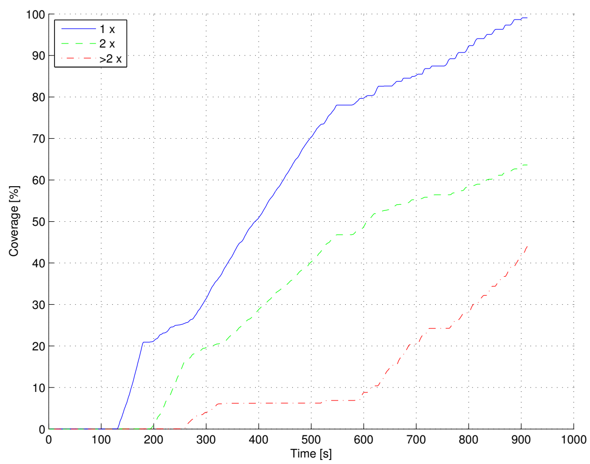


Fig. 12. The inward spiral and shifted spiral took 12 min and covered 99% of the area, blue line. Approximately 64% of the area was covered twice, green line, and less than 44% was covered more than twice, red line.

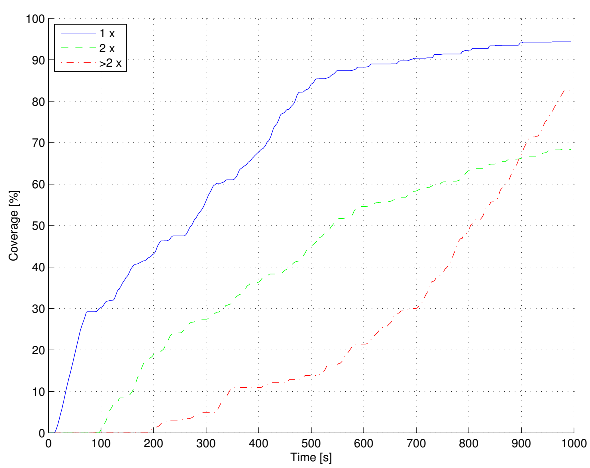


Fig. 13. The inward spiral and shifted spiral took 15 min and covered 95% of the area, blue line. Approximately 70% of the area was covered twice, green line, and more than 80% was covered three times or more, red line.

points more closely. One promising solution is to combine it with Road Maps [18].

Acknowledgments

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