Cooperative Coverage by Multiple Robots with Contact Sensors

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***Abstract*—Cooperative coverage by multiple robots with contact sensors is studied in this paper. Multiple robots Internal Spiral Coverage algorithm is presented to overcome the sensing limitation of the robot whose sense range is the radius of the body. The algorithm guarantees complete coverage by repeating covering portion of the environment and setting the GATE grids. The algorithm is also robust in that even if there is only one robot without catastrophic failure it can complete the coverage. The competitive analysis is also made and the upper limitation of the competitive factor is presented. The simulation test and real experiment prove the feasibility of the algorithm.**

***Keywords*—coverage, multiple robots, contact sensors**

I. INTRODUCTION

Area covering is common in many applications of mobile robot, such as de-mining, floor cleaning and map building. In these tasks the robot is required to pass an end-effector over all the free space. In unknown environment the robot must use its onboard sensors to plan a path online that reaches every point, which is known as sensor-based coverage [1].

Using multiple robots can improve efficiency and reduce the working time because the robots are working in parallel. Furthermore when a robot encounters catastrophic failure, other robots can take its place and complete the task. In addition multiple robots coverage is robust, more and more researches have been made in recent years.

Multiple robots coverage can be grouped into two types: off-line and on-line coverage. In off-line coverage, the robots have a-priori knowledge of the work-area. And the route for every robot is planned in advance. Hazon and Kaminka suggested off-line multi-robot coverage algorithms based on single-robot off-line STC (Spanning Tree Covering) algorithm [2]. They allocate the planned path to robots represented by grids. All the robots communicate to each other in covering. If a robot stops because of failure, the one next to it will finish the task after its own has been completed. Hazon and Kaminka also discussed the impact of the initial positions of robots on the covering efficiency.

Rekleitis et al [3] use multiple robots that have local communication ability in on-line coverage. Two robots explore the environment and decomposition cells that can communicate only when they are within line of sight of each other. Other robots cover the cells with back-and-forth motion. Wagner et al [4] use ant-robotics to cover the free space. They use the pheromones left by each robot to communicate. In these methods either the map is known in advance or the robot has external range sensors to detect objects some distances away. None of them is fit for the simple robot. Simple robot is one equipped only with a contact sensor and internal odometry sensors [5]. Multiple simple robots coverage is studied in this paper, which is based on the ISC (Internal Spiral Coverage) algorithm presented by the authors [6].

This paper is divided into the following sections: Section II introduces the ISC algorithm and section III describes the MISC (Multiple robots Internal Spiral Coverage) algorithm. Section IV discusses the completeness of the method and the robustness of the system. The competitive analysis is also made in the section. Section V contains simulation and real experiments. Finally section VI presents the conclusions.

II. SINGLE ROBOT ISC ALGORITHM

A circular simple robot is used in ISC algorithm with contact sensors on front, left, right side and odometry sensors. There are three assumptions in the algorithm: First, The size of the robot is far smaller than the environment. So the environment can be represented by the grids that have the same size of the robot. The grids which are partially covered by obstacles are discarded. And the robot can move only in directions orthogonal to the current grid. Second, once the robot enters a grid it has covered the grid. Third, the global coordinate of the robot can be calculated accurately by odometry (the real robot's position is adjusted by the infrared sensors in some extend, which is illustrated in section V). There are two stages in ISC: the boundary exploration and on-line coverage. In boundary exploration, the robot starts from any vertex of the environment, keeps the right side contact sensor touching the boundary, and moves in counterclockwise until it reaches the initial position. In the exploration, it sets the value of the grid within which the right side contact sensor is to 0, which means the grid is boundary or obstacle and can not be covered. Sets the grid value to 1 which the robot passes, which suggests the grid has been covered. And sets the grid left to the robot to 2, which is to be covered in the next loop, i.e. the planned path. So when the exploration is over, the boundary of the environment is got, a loop near the boundary has been covered and the next loop path has been planned. Afterwards it turns to the on-line coverage stage.

In on-line coverage stage the robot follows the path generated in exploration stage, i.e. the continuous grids whose values are 2. In covering the robot changes the grids' value from 2 to 1 after passing them, and sets the grids left to the robot to 2 that have not been set values. So after the second loop is over the third loop path has been generated. And the robot can cover the entire region in such a manner.

If there are obstacles within the environment, they will block the path and disconnect the grids 2. But in the following loop the robot will encounter them by the front contact sensors. The robot moves around the obstacles, keeping the sensors on the right side touching the boundary of the obstacle till there is a grid valued 2 in front of it, and goes on covering along the planned path.

The robot can cover the environment completely using the spiral manner from the outer to the inner if the environment is made up of a single rectangular room. But in the complex environment that is made up of two rooms, problem will arise. As shown in fig. 1, the free space at the entrance is narrower than both sides (Room A and Room B). And it will be covered completely first, leaving both sides uncovered completely. So we introduce the GATE grid.

Definition 1: The GATE grids are those that have already been valued 1 or 2 before to be set value 2, with grids uncovered both in front and back of the robot.

As shown in fig. 1, when the robot enters room A from B, and intends to set the grids to 2 on PQ, but it finds that those grids have already been valued 2, so the robot sets them GATE grids, then covers room A first. Without setting the GATE grids, the robot will cover QP after passing OQ and sets QP to 1, which disconnects the uncovered regions in room A and B. As a result the robot will no longer enter room A and leave it uncovered. So once there are GATE grids, the robot remembers their positions and covers one side of them. When there is no grid whose value is 2 in that side, it means the robot has finished covering the selected side. Then it returns to the GATE grids and goes on covering in the other side. The algorithm terminates when there is no grids valued 2 in the whole environment, which suggests it has been covered completely.

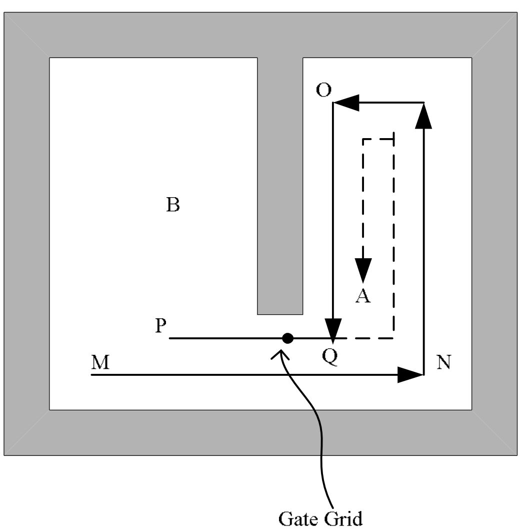


Figure 1. GATE grid

III. MULTIPLE ROBOTS INTERNAL SPIRAL COVERAGE ALGORITHM

In MISC, the three assumptions are also valid, and the grid map is shared by all the robots, i.e. each robot tells others the planned and covered grids by its own. A set of k robots are used in the coverage. Table 1 illustrates the top level of MISC algorithm. There are also two stages in MISC.

A Boundary exploration in MISC

The k robots are scattered randomly along the boundary and move at the same time in counterclockwise, recording the information about the boundary, as shown in Table 1 from step 1 to step 3. The k robots break up the boundary into k sections. The shortest section is denoted as m, and is explored by robot m. When robot m arrives at the initial position of robot m+1, it will find in the shared map that the front grid has been valued 1, and the left front grid valued 2. So robot m terminates boundary exploration stage and turns to on-line coverage along the path planned by robot m+1. All other robots will turn to on-line coverage arriving at the initial position of the next robot.

B Multi-robot on-line coverage

Once turning to online coverage stage, every robot (for example m) will move along the path planned by the next robot (m+1) and plan path for the former robot (m-1), as shown in Table 1 from step 7 to step 8. When the robots run into obstacles, they turn to starboard following obstacles until the front grid valued 2, and they continue the on-line coverage.

Some environment has irregular shapes, as shown in fig. 2. There is a bulge on the boundary. When the uncovered region in the bulge satisfies $CD > 3d$ (CD is the height of uncovered region, d is the side length of each grid), the coverage is executed as above. If $CD = 3d$, after robot m moving

Table I TOP LEVEL OF MISC

Step 1: Arbitrarily place the k robots along the boundary and start exploration
Step 2: **While** not finding the covered grid in the front **do**
Step 3: Record the information about the boundary, the covered girds and plan the path
Step 4: Terminate exploration and turn to online coverage
Step 5: **if** obstacles are found by the front sensor **then**
Step 6: Move around the obstacle until the planned path is ahead
Step 7: **While** there is planned path near the robot **do**
Step 8: Move along the planned path, record the covered region and plan path on-line
Step 9: **if** no GATE grids are set **then**
Step 10: Search for the nearest grid valued 2 and move to it, goto 7
Step 11: **else** move to GATE grid, goto 7
Step 12: Stop

along $B \to C \to D \to E$, the uncovered region is a blind valley with height of d. And when robot m-1 reaches the vertex C, it will find there is no planned path, m-1 searches for the nearest grid with value 2 in the shared map. (In fig. 2 it is the grid at E.) Robot m-1 moves to that grid and continues the coverage. If $CD = 2d$, robot m moves along $B \to C$ and returns along $D \to E$. If the distance between robot m and m-1 is so short that robot m-1 reaches position E before robot m finishes $D \to E$, robot m-1 will cover along $E \to D$. As a result the two robots must meet in DE , and both find there is no planned way near them. They look for the nearest valued 2 grid and move to it. The target in fig. 2 is the grid next to E. So robot m-1 turns back and moves along $D \to E$, and robot m still moves forward, as shown in Table 1 step 10. For the convenience of statement, we exchange the sequence number of m-1 and m. When the new robot m arrives at E, it will find the path planned by m+1 and goes on covering, and robot m-1 follows the path planned by robot m.

The same problem will arise near the entrance of every room, so the GATE grids are needed. But every robot sets its own GATE grids. As shown in fig. 3 the GATE grids are set in PQ when robot m enters room A along MN, and room A is covered first. When robot m-1 arrives at the point P, it will move along PS instead of PQ because PS is the planned path while the values in PQ are not 2. When the coverage in room A is finished, robot m returns to its own GATE grids and covers them from the end to the start. If there is a path near the first GATE grid, it suggests robot m-1 is so far away from

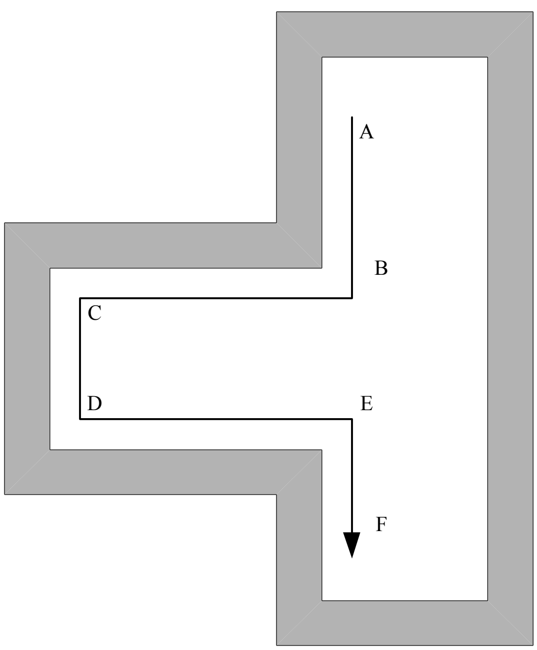


Figure 2. Coverage of protrusions

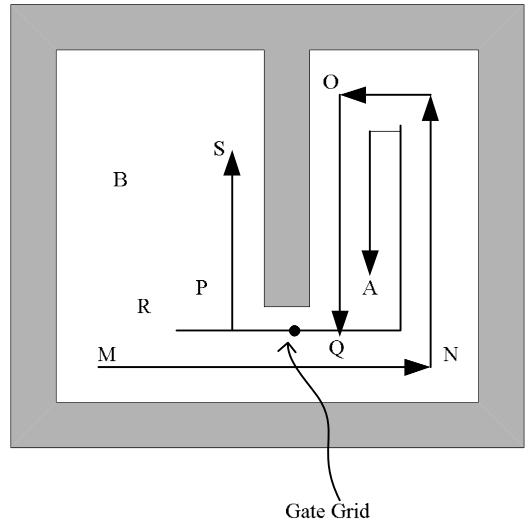


Figure 3. GATE grid in multiple robots coverage

m that it has not reaches P, robot m takes its way along PS. On the contrary if there is no way near the first GATE grid, it means that robot m-1 has passed PS and valued them 1. In that case robot m will have to stop for not finding path. It is obvious that there is at least one robot which will not stop at the GATE grid, so MISC algorithm can cover the environment completely. When there is no grid valued 2, all the robots stop and the algorithm terminates.

IV. ALGORITHM ANALYSES

In this section we will discuss the covering completeness and robustness of the algorithm and make the competitive analysis.

A The covering completeness of MISC

MISC algorithm can cover the rectangular environment completely from the outer to the inner. When there are no obstacles in the environment, robot m will move along the path planned by m+1 without repetition, and plan the path for m-1 at the same time, except for the case of the T-shape blind valley or GATE grids. It is known from section III that the algorithm can recover from blind valley to normal coverage by repeated covering partial of the blind valley. And the path planned by robot m-1 for m-2 is a straight line along $A \to B \to E \to F$ in fig. 2, which has not any relationship with the blind valley at all.

When robot m enters a narrow space and sets the GATE grids, it will first finish the complete coverage of one-side. The GATE grids can prevent other robots from entering the same side. So the GATE grids and the region covered by robot m seem as obstacles to other robots that can not be visited nor need cover. The algorithm solves the problem that would disconnect the two uncovered regions by setting GATE grids. If there exists a path when that region and the GATE grids have been finished, robot m continues to cover it, else it stops.

If there is an obstacle within the environment and robot m+1 does not find it, it must lie in the way of robot m. When robot m knocks into it, m can move around it until returning to the planned path. The path planned for robot m-1 is a detour around the obstacle. In the subsequent covering it will not have any affection any more. So without encountering catastrophic failure, the robot only stops at the GATE grid or after the environment has been covered completely. We know from section III that there is at least one robot that will not stop at the GATE grid. So MISC algorithm can cover the environment completely.

B Robustness of the system

In covering every robot moves along the grids valued 2, and at the same time sets the left girds to 2. So it can not tell which robot plans the path, even does not know how many robots are covering the region. The merit is obvious: When one robot fails to move, it has no any affect on others. If robot m stops in accident, robot m-1 will treat it as an obstacle and move around it when m-1 arrives at the place where robot m breaks down. Then robot m-1 moves along the path m is following. And robot m will not affect the coverage any more in the future. It will not disturb the coverage even adding or taking away a robot in covering. So MISC can finish the task even if there is only one robot without failure.

C Competitive analysis

An algorithm is competitive if its solution to every problem instance is a constant times the optimal solution to the problem with full information available [7]. The ideal optimal solution in coverage is complete coverage without any repetition. (But in some conditions there is no such desired optimal solution, e.g. the "F" shape environment with width of 1). So the length of the ideal optimal coverage path for the environment with free space C is C-1.

The boundary of any environment may be treated as the standard rectangle with some concavities and protrusions on it. And the inner obstacles are similar to concavities for the uncovered region when they are detected. So the repetition is caused by two sets: the concavities and the protrusions.

The repetition caused by concavities is as fellows. When the free space near the concavity is narrow enough to make the GATE grids, the robot covers one side first. The repetition length is the number of the grids between the terminated spot and the GATE grid. In fig. 4 the length equals to the number of the grids between E and G. Now we assume it takes k loops to set GATE grid at G, and m loops to cover room A till terminates at E.

$$\|GE\| = \|GX\| + \|XE\| = GX + XZ - EY - YZ$$
$$= m + (l + k) - m - k = l < H \qquad (1)$$

In (1) l is the length of the concavity, H is the perimeter of the concavity.

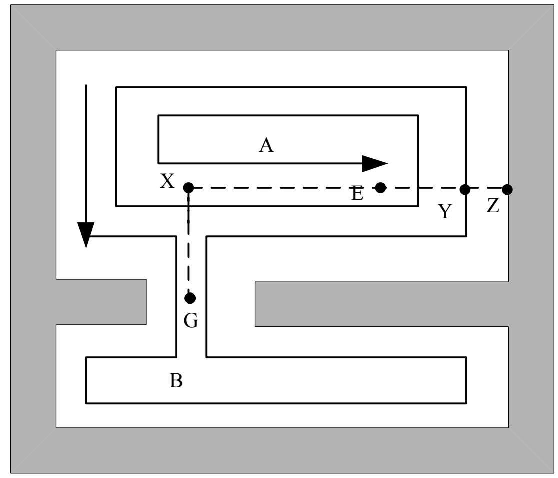


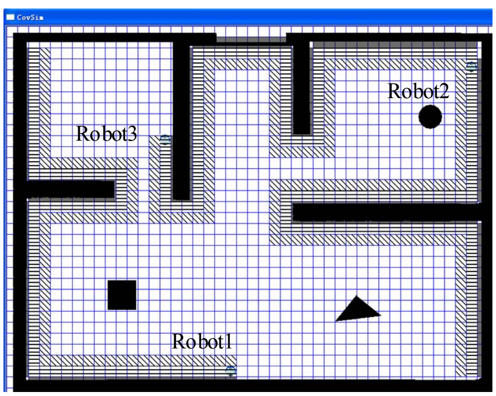
Figure 4. Repeated coverage caused by concavities

The worst case in protrusions is that two robots move into the protrusion side by side and arrive at the end at the same time to find that there is no way. Both have to move back and cover the protrusion twice. If the length of the protrusion is l, the repetition will be 2l<H. We denote H as the sum of the perimeters of the concavities, the protrusions and the obstacles. Then the upper limitation of repeated coverage in MISC is H. So it takes C-1+H steps at the most to cover the environment completely, and the competitive factor is 1+H/(C-1).

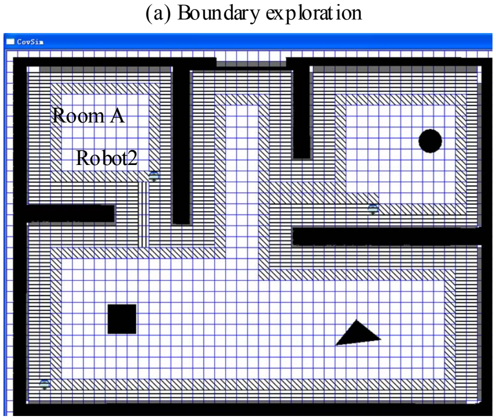
V. EXPERIMENTS of MULTIPLE ROBOTS COOPERATIVE COVERAGE

The simulation test and real experiment of multiple robots cooperative coverage in indoor environment are made in the paper. In the simulation test the obstacles can be detected only when the robot touches them and there are pixels overlapped. The environment is 900 by 700 pixels, and is made up of three rooms. The space at the entrance is narrower than both sides. And several obstacles are scattered in the environment at random. Three round robots are used whose radii are 10 pixels. We know from section III that the larger the distance between two robots, the smaller the possibility is that the front robot stops at the GATE grid. So we try to populate them evenly on the boundary. In the test they are placed at the three corners and start exploration at the same time. As shown in fig. 5a robot 2 turns to on-line coverage mode at the initial position of robot 3. The solid grids represent the obstacles, and the horizontal lines correspond to the covered region, the sloping lines mean the planned path. In fig. 5b robot 2 enters room A and sets the GATE grids which are represented by vertical line. Then robot 2 will cover room A completely and robot 1 and 3 will not enter room A. In fig. 5c when room A and the GATE grids are covered completely, robot 2 returns to the first GATE grid to find that the path has been covered by robot 1 and there is no way to move, it has to stop. With covering going on, robot 3 detects the triangular obstacle, it detours it using the side sensors. The trajectory of every robot in the coverage is exhibited in fig. 5d. Robot 1 moves along the black solid line, robot 2 along the black dashed line and robot 3 along the gray solid line. There are 1117 free grids with the sum perimeter $H = 144$ in the environment. It takes robot 1 493 steps to cover 454 grids. The repetition rate is 8.59%. Robot 2 uses 230 steps to cover 223 grids. The repetition rate is 3.14%. And robot 3 uses 456 steps to cover 440 grids with the repetition rate 3.64%. The system repetition rate is 5.55% with the competitive factor upper limitation 1.13.

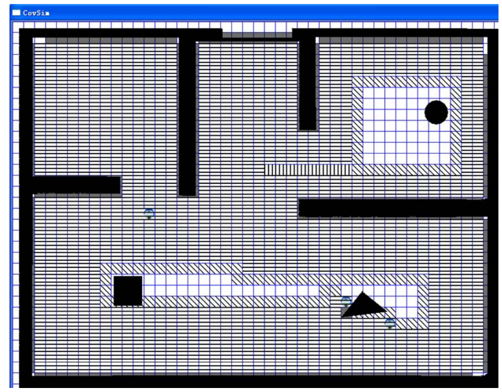
For real robot, the odometry error will accumulate and the robot will get lost at last. Yet we can correct the position error by the infrared sensor. As shown in fig. 6, the charge station emits infrared signals in a narrow opening angle (about 5 degrees, like a line). There are four receivers on the robot, each of which can receive the infrared signal in a field of 90 degrees. So the robot can receive the signal from any direction. When the robot moves in front of the charge station, it can receive the infrared beam, so it can correct its position error in some extend. We use two robots to cover a room of 8.2×5.5 meters with one box in it. The charge station is at the center of one of the long boundary. And the robots start from the two corners on the diagonal. When the robots receive the infrared, the odometry error can be corrected. In the experiment 92.7% of the region has been covered with 9.43% repetition.



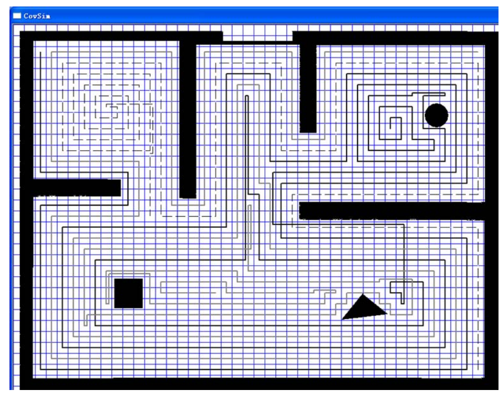
(a) Boundary exploration



(b) Setting GATE grids



(c) Detouring the obstacles



(d) The trajectory of every robot

Figure 5 Simulation test

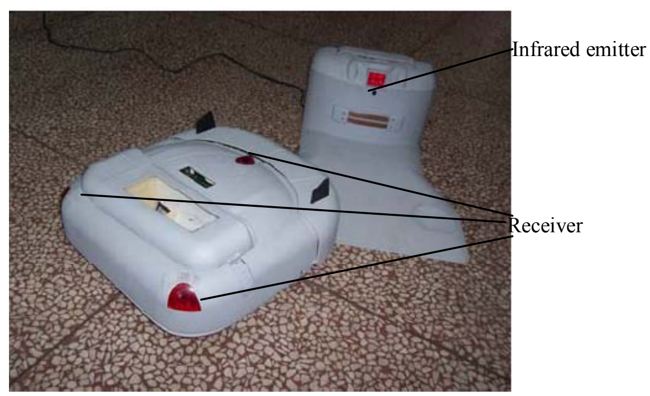


Figure 6 The robot and the charge station

VI. conclusions

Cooperative coverage by multiple simple robots is studied in the paper, and the MISC algorithm is presented. The algorithm guarantees complete coverage by repeating coverage of partial region and setting GATE grids. The path is planned online only using the shared map and not taking effect of other robots into consideration, which improves the robustness of the system. It can finish the coverage so long as one robot can work. And the upper limitation of the competitive factor is also provided. The algorithm realizes simply and is fit for the simple robot.

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