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Article

Environmental Protection by Robots

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Abstract: Mobile robots are increasingly applied in critical domains such as environmental protection, where precise coordination is essential to avoid collision and ensure effective area coverage. In luminous robot models, coordination is typically achieved through visual cues, as robots lack memory, communication, or global knowledge of group size. The fully-synchronous model provides an opportunity to exploit predictability in robot behavior to develop efficient protection algorithms. Although several approaches address robot movement coordination, few achieve optimality with minimal light usage while ensuring non-overlapping trajectories in unknown-sized teams. This study proposes an algorithm that ensures all robots reach the environment's boundary without overlapping and without prior knowledge of total robot count (n), using only two lights (black and gold) in a fully-synchronous setting. The algorithm successfully guides robots from arbitrary starting positions to non-overlapping positions along the environment's circumference in O(n)O(n)O(n) rounds. Robots transition their light from black to gold upon reaching their final destination, providing a visible indicator of task completion. Unlike prior methods that assume robot chirality or require more complex communication or sensing capabilities, this solution is optimal in light usage and functions without coordinate agreement or global information. The results offer a practical and efficient strategy for autonomous swarm deployment in scenarios demanding high coordination with minimal resource use. Future work may adapt this approach to asynchronous modes or non-luminous robot models to broaden its applicability.

Keywords: Environmental Protection, Mobile Robots, Luminous Model, Robot Coordination, Non-Overlapping Movement, Fully-Synchronous Mode, Two-Light Algorithm, O(N) Complexity

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1. Introduction

Robots are machines with some capabilities that are divided into two types static and mobile robots. Static robots cannot move from a place to another place. However, mobile robots are the robots that can move from a place to another place so that we used mobile robots in our work to facilitate the solution of our algorithm because of their flexibility in the motion. The robots are used in may aspects such as safety, protection, environmental protection, surveillance, good and data delivery, cleaning, medicine, technology, engineering, physics, nanotechnology, monitoring, and ..etc. These many important uses make a lot of sense in developing society [1].

Our system consists of n ≥ 1 robots operating in the Euclidean plane in two dimensions. We present an algorithm to solve the problem of utilizing the robots in the environmental protection. The robots follow the luminous model where every robot has a light [2]. Except the lights existing, the robots are oblivious that are no memory usage, no identifiers, no markers, no control, no coordinate systems agreement, and no communication. The robots use the cycles of (LCM) where they look, compute, and move [3]. As soon as the robot is turned on, it looks about and takes a picture of it. The destination point is then calculated (computed). If its destination differs from its present location point, it ultimately moves to it (move). To tackle the challenge, every robot uses the same algorithm [4].

There are three modes of activation of robots. The first mode is fully-synchronous where every robot turns on and does its LCM cycles at the same time. The second one is semi-synchronous that is very close from the first mode, but some of robots turn on at the same time while the others are not. Therefore, round is used instead of time in both first two modes. At the end, we have the last mode which is asynchronous mode where each robot is turned on in different time. It is unsure how long the look, compute, move cycles will delay, but the time is finished. The classical oblivious robots paradigm has been the subject of extensive research [5]. In our case, the robots follow the luminous model where every robot has a light [6]. Except the lights existing, the robots are oblivious. Data transmission, intruder detection, exploration, coverage, and symmetry breaking are just a few of the numerous robot applications that use this paradigm [7].

Some of the works used the unobstructed visibility in their algorithm solutions. They supposed that the robots r0 and r2 can observe each other even if a third robot r1 is present within the line segment connecting r0 and r2 since they assumed the point robots [8].

The recent work studies the problem of how protecting and monitoring an environment by using the robots when the vision of robots is unobstructed where the robots move on the boundaries or circumference of the environment from any arbitrary configuration or environment without overlapping with each other. Where there is a point shared between the robots at any time, then these robots are overlapped. As a result, we present an algorithm to get a solution to our problem. In our algorithm, the robots are moved to the boundaries of the environment to monitor and protect it without preventing the visibility of each other robot in the fully synchronous mode where n, the entire number of robots is not known by each robot. The problem is solved in luminous model using two lights in the color set black and gold [9].

According to our idea, there is no solution to the this problem of robots in the luminous model under the conditions that we used without any overlapping among robots. The solution of our algorithm uses two colors which is professional. While the algorithm is executed, the robots disagree regarding which axes to align. n is not award by the robots. O(n) rounds are used by our solution when the mode of robots' activation is fully-synchronous [10].

1.1 Related Work

Two models are available. The conventional model, which does not use lights, and the luminous type, which equips robots with visible lights [11]. The robots' luminous model allows them to change their lights by utilizing a color set that contains several hues. The light does not go out when the cycle is over. With the exception of the lighting model's light idea, the two models function similarly. When there is only one color in the set of colors, the classical model and the lights luminous model are comparable [12]. When the issue is resolved, the lights model aims to determine how to reduce how many colors there are.

When addressing the issue, some earlier research looked at the classical robot model, while others looked at the robot lights model [13]. The majority of earlier studies took into account point robots once the issue was resolved.

The related work to ours according to the idea of environmental protection by robots is by Alsaedi et al that creates a pattern of robots using luminous model that assists in protecting the environments [14].

2. Materials and Methods

We have a collection of n ≥ 1 obscure robots that work in the Euclidean plane: R = {r1, r2, r3, . . . , rn}. We suppose that the robots are not aware of n throughout the algorithm's execution. Every robot in the system has a unique coordinate system and is aware of its location in relation to that system. There may be disagreements among robots regarding the orientation of their coordinate systems, meaning that they do not have a similar understanding of direction. The robots are equipped with cameras to capture images, and their visibility is unrestricted [15].

We suppose that the robots r0 and r2 can observe each other even if a third robot r1 is present within the line segment connecting r0 and r2 since we assume the point robots [16].

An externally visible light that can take on any color from a static set C of colors is installed on each robot ri. Every robot in R has the same set C. All robots visible to r at time t can observe the hue of robot r's light at that moment.

A set of n robots in C × R2 that specify the robots' colors and locations is called a configuration C. Let the configuration at time t be represented by Ct. The configuration Ct for robot ri, or the set of robots C × R2 of the robots visible to ri, is represented by Ct(ri).

The robots use the cycles of (LCM) where they look, compute, and move [16]. As soon as the robot is turned on, it looks about and takes a picture of it. The destination point is then calculated (computed). If its destination differs from its present location point, it ultimately moves to it (move). To tackle the challenge, every robot uses the same algorithm [17].

The mode of the activation of robots that we use is the first one which is fully-synchronous where every robot turns on and does its LCM cycles at the same time.

We say that the problem gets the solution if all the robots move to the circumference of the environment to monitor and protect the environment without overlapping with each other and changing their lights to gold color. These movements of robots can be done without enlarge the environment, i.e., in the same given area of the environment which is the challenge. The problem is solved without any assumptions such as chirality where every robot has to agree on the direction of robots and without requiring to determine the entire number of robots which is n in our case [18].

3. Results and Discussion

In this section, we present our algorithm that gets the solution of the problem of environmental protection by robots. we have a system of n ≥ 1 of luminous robots that follow rigid movements in the fully-synchronous mode. Our solution requires two colors while solving this above problem C = {black, gold}. The black robot represents the robot in its initial instance or any other middle instance. However, the gold robot represents the robot in its final instance which is in the circumference of the environment [19].

We have the following environment as an example, see Figure 1. Initially, all robots have black light.

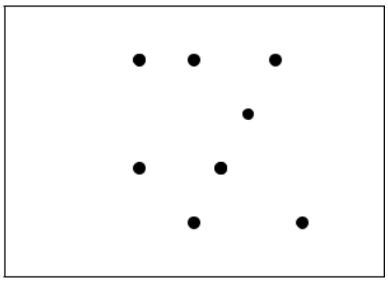

Figure 1. An Example of an Initial Environment.

Each robot in the initial environment starts to move to be in the boundaries of this current environment. First of all, each robot determines the eligible edges that can move through without overlapping with other robots. Then, the robot chooses the closest eligible edge from the collection of its eligible edges. It checks that it will not overlap with other robot, i.e., it will not share a point with other robot in its way while moving to its final location on the closest eligible edge of the circumference of the given environment. It moves straightly to its final location if there is no other robot in its way. Since the robot has a camera with 360 degree of visibility, so it can observe if there is a robot in its way until getting its final location. If there is a robot in its way, so it can move one unit to the left or right according to the space available in its eligible edge, then it moves straightly to its final location on the edge. If there is no space on that closest eligible edge, then it chooses the second closest eligible edge from the collection of its eligible edges ensuring that no overlapping among robots. The robot has a light with black color in the initial instance until getting its final location. However, it turns on its light to gold color when it reaches its final location on the circumference of the environment. The initial and final environments have the same area. When each robot has a light with gold color, then the problem is solved since each robot can observe its light and other robots' lights. Therefore, each robot can determine when the problem is solved by observing each robot's light with gold color in the circumference of the given environment [20]. Figures 2, 3, 4, and 5 explain the robots movement to the circumference of the given environment with changing their lights to gold.

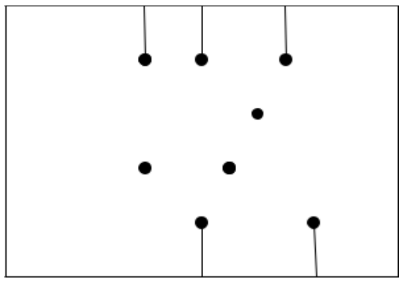

Figure 2. Step one of Robots Movement.

Figure 3 illustrates the second step in robot movement, where those positioned on the environment's perimeter activate a gold light signal. This color-coded indication is crucial for distinguishing boundary robots from internal ones, facilitating coordinated behavior and spatial awareness in distributed robotic systems operating within constrained environments.

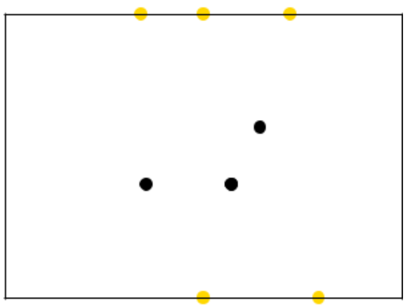

Figure 3. Step Two of Robots Movement: The Robots on The Circumference of The Environment Set Their Lights to Gold.

Analysis

In this section, we analyze our algorithm. We prove that our algorithm solves the problem of protecting the environment by robots in a linear time complexity without overlapping. Two colors are used. We start to prove the solution of our algorithm [21].

Lemma 1. We have any initial environment C0; there is no overlapping of robots occurs until all robots are on the circumference of the environment, meaning that no robots inside the environment.

Proof. Any robot ri inside the initial environment with light black does not overlap with any other internal robot because the move of robot ri is perpendicular to the closest edge, and there is enough space on the edge for the robot to move through it because the robots are points. The robots moving through different edges of the given environment do not overlap since those robots are the closest robots to those edges. We then prove how each robot ri chose the closest eligible edge is able to move to the circumference of the given environment [22].

Lemma 2. There exists a round such that the robots inside the given environment that are closest to their eligible edges are able to move on the boundaries of the given environment changing their lights to gold [23].

Proof. By Lemma 1, the robot ri does not overlap with other inside robots while it tries to move to its closest edge of our given environment. By the same Lemma 1, there is no overlapping for robot ri while it moves to the closest eligible edge. Since the movements are rigid, ri reaches its computed location on the edge once it moves and changes its color to gold [24]. In the following statement, we have to count the number of lights or colors required by our solution.

Lemma 3. Our algorithm is completed requiring two colors. Proof. By Lemma 1 and Lemma 2, each robot requires at most two colors which are black and gold, and the lemma follows.

We next prove the time that is spent while executing the algorithm [25].

Figure 4 presents the third step in the robots' movement process. Robots located internally begin moving vertically toward the boundary robots with gold lights. This behavior demonstrates a coordinated attraction mechanism, enabling interior robots to align with the perimeter formation and progress toward achieving a predefined spatial arrangement in a distributed system.

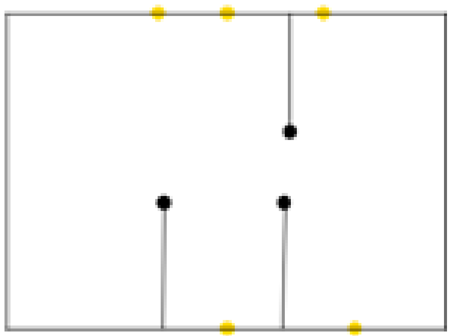

Figure 4. Step Three of Robots Movement.

Figure 5 illustrates the final stage of the coordination process, where all robots successfully reach the environment's boundary and activate their gold lights. This uniform distribution along the perimeter reflects successful convergence, highlighting the effectiveness of decentralized algorithms in guiding robot swarms to structured configurations in bounded environments.

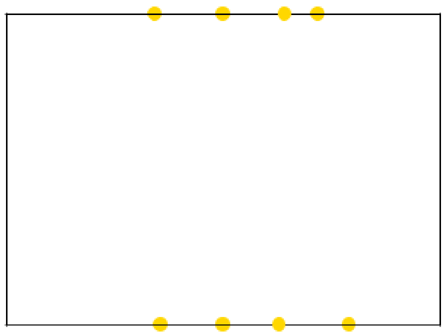

Figure 5. All Robots are on The Circumference of The Given Environment with Gold Lights.

Lemma 4. When all n robots move to the circumference of the given environment, O(n) rounds are spent until getting the solution of our algorithm [26].

Proof. Since in the worst case, we have all robots inside the given environment. Each robot moves perpen-dicularly to its closest eligible edge needing only one round. If the robot senses that it may overlap with other robots, it moves one unit to the left or right according to the available space on its way by its visibility before its movement to its final location on the boundaries of the given environment. This requires another round. Therefore, in the worst case each robot requires at most two rounds unit moving to its final location. This gives as a result O(n) is the entire time required by our solution [27]. Ultimately, we conclude with the following theorem.

Theorem 5. In a fully-synchronous mode, our approach uses two colors to solve the Environmental Protection by Robots issue in O(n) rounds without overlapping [28].

4. Conclusion

We presented an algorithm that got the solution for the problem of Environmental Protection by Robots for a system of n robots in the luminous model without overlapping. We used the fully-synchronous mode and rigid movements in our solution. O(n) rounds are required by our algorithm to get the solution of the problem. In this problem, we used two lights which is professional and optimal solution since any problem in this model needs at least two lights to be solved.

For future work, it is motivating to extend and develop our algorithm to get the solution of the problem in the traditional model without lights and using other modes of activation which are semi-synchronous mode and asynchronous mode.

This study presented an efficient algorithm for solving the problem of environmental protection using luminous mobile robots operating in a fully-synchronous mode. The algorithm ensures that all robots reach the circumference of a bounded environment without overlapping or requiring knowledge of the total number of robots. A key finding is that the use of only two colors black for initial and transitional states, and gold for final positions proves sufficient and optimal for achieving coordination, visibility, and termination detection. The algorithm guarantees O(n)O(n)O(n) round complexity, thereby affirming its scalability and computational efficiency. These results contribute to the growing body of knowledge on robot coordination in decentralized systems, particularly under limited communication capabilities. The implications of this work extend to applications in automated surveillance, perimeter monitoring, and disaster zone mapping, where robots must organize autonomously with minimal resources. Future research could extend this model to semi-synchronous or asynchronous activation modes, and explore the feasibility of achieving similar coordination in non-luminous or classical robot models, thereby enhancing robustness and applicability in more diverse real-world environments.

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