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A Fault Tolerant Model for Geometric Patterns of Swarm Agents

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Abstract— Swarm robotics is based on the characteristics displayed by the insects and their colony and is applied to solve real world problems utilizing multi-robot systems. Research in this field has demonstrated the ability of such robot systems to assemble, inspect, disperse, aggregate and follow trails. A set of mobile and self-sufficient robots which has very restricted capabilities can form intricate patterns in the environment they inhabit. However, coordination of multiple robots to accomplish such tasks remains a challenging problem. Pattern formation is one of typical problems in the field of multi-robot cooperation. Compare to traditional multi-robot coordination algorithm, the method based on swarm robots to solve the issue of pattern formation has better scalability and dynamic adaptability and robustness. The swarm robots have only local perception and very limited local communication abilities, so one of the challenging tasks while designing swarm robotic systems with desired collective behaviour is to understand the effect of individual behaviour on the group performance. So fault tolerance is another issue to deal with. This paper reviews the background knowledge and some noticeable achievements in the field of pattern formation and fault tolerance.

Keywords—Swarm robotics, pattern formation, swarm intelligence, particle swarm intelligence, fault tolerance

I. INTRODUCTION

In the last decade, robotic pattern formation and formation control have experienced a rise of attention along with the advances in multi-robot systems. The applications of pattern formation are broad, and include multi-robot navigation tasks for exploration, escorting and rescue missions, alignment of aerial vehicles, or cooperative control of mobile sensor networks to maintain surveillance or coverage. The pattern formation task involves the assignment of robots to goal positions that define the final pattern, but also control the robots to actually establish the formation. Typical work on pattern formation in robotics like focuses on the positioning of the robots in a specified pattern and measures against the accuracy of the patterns achieved, as the main goal is the final robot formation, which often is the basis to accomplish another task.

One of the challenging tasks in the Pattern Formation of swarm robots is *Fault Tolerance*. Fault Tolerance is increasingly important in modern autonomous and industrial robots. The ability to detect and tolerate failures allows robots to effectively cope with internal failures and continue performing designated tasks without the need for intermediate human intervention. To support these fault tolerance capabilities, methods for detecting and isolating failures must be perfected. Swarm of robots can form different geometric patterns like any polygons example circle, square, triangle, rectangle etc. By pattern formation, we mean both pattern generation and pattern maintenance. The swarm consists of a group of robots that can assemble themselves in a specific pattern. Since the communication range of the swarm robots is very weak, whenever a robot gets faulty it could affect all the other robots in the formed pattern. The aim of this paper is to study a self-configurable framework for a large-scale swarm of autonomous robots to tolerate the fault occur in the robot, which is positioned in some kind of pattern and to self-organize the team of robots performing the given task in a specific pattern. For this purpose, this paper indeed intends to provide a simple decentralized model such that for a pattern formed by group of swarm robots, it can tolerate the fault occur in one or more faulty robots. Using this proposed model, the remaining non-faulty robots in the pattern can communicate and restore the previously formed pattern with less number of robots.

This paper is organized as follows, Section I contains the introduction of pattern formation and fault tolerance in swarm robots, Section II contain the related work of circle formation, pattern formation and fault tolerance in swarm agents, Section III contain the problem statement, Section IV contain the solution methodology, section V explain the proposed work with flow chart, describes the fault tolerance model, implementation and Section VI concludes research work with future directions.

II. RELATED WORK

A fundamental problem in swarm robotics is pattern formation by a group of mobile robots. These include simple patterns like line, circle, square, triangle, etc. Using centralized method these tasks are trivial, but this is not the case in distributed methods. Until now, the amount of research done in pattern formation is immense but only a few works studied the fault tolerance in pattern formation. And the literature on fault tolerance in robotics has focused mainly on small-scaled techniques that are targeted toward a scenario with a limited scope. This section reviews the studies about fault tolerance in multi-robot systems.

In the literature different works are dealing with pattern formation, Suzuki and Yamashita (1999) [7] propose a non-oblivious algorithm for the formation of a regular polygon in the unlimited visibility case considering the computation models both semi-synchronous and fully-synchronous. In other words, the robots eventually reach a configuration in which they are arranged at regular intervals on the boundary of a circle. This is achieved with local knowledge of the environment, however, more than one robot can be taking up the same position and it is assumed that the time for performing the process can be infinite. Here no discussion about fault tolerance is made.

Defago and Konagaya (2002) [10] present a method for circle formation based on extensions of the Suzuki model which consists of two algorithms executed one after the other. The first algorithm places the robots along the circumference of a circle and the second uniformly distributes the robots along the circumference. In the circle formation algorithm, the robots are initially in arbitrary positions. The goal of these robots is to determine the *smallest enclosing circle (SEC)* and then move to occupy positions along this circle. This method is computationally complex and how the SEC can be practically determined in real time is not stated. Also it hasn't discussed robot crash & failure effect in the system.

In order to reduce the complexity of the above algorithm, another method was developed by Markou et al. (2004) [19]. In this method, once the SEC is computed, a given robot determines the point on the circumference of the SEC,that is closest to it and moves towards this point. When all the robots have taken positions along the circumference, they spread along the circumference. This method is closer to our work but it does not about fault occurrence & tolerance.
S. Nouyan and M. Dorigo (2004) [4], presented the paper on chain based path formation, in which the group of robots has to form a chain between two objects Nest and Prey. They highlighted that the robot's behaviour can be detailed as *Search, Explore, Chain, and finished*. In case a robot becomes faulty in a chain, they will move back to the Nest, from where they restart to form a new chain.

Winfield, A.F.T. and Nembrini, J. (2006) [14] explored fault-tolerance in robot swarms through Failure Mode and Effect Analysis (FMEA) and reliability modelling such as load sharing approach or multi-state approach.

Noa Agmon and David Peleg (2006) [30] presented a systematic study of fault-tolerant algorithms for the problem of gathering N autonomous mobile robots. A gathering algorithm, executed independently by each robot, must ensure that all robots are gathered at one point within a finite time.

Bingu Shim, Beomho Baek, Suntae Kim and Sooyong Park [17] presented a systematic approach to facilitate the selection of appropriate robot fault-tolerance techniques on the basis of the context in the robot domain. They had applied the approach to build fault-tolerance architecture for a robot platform.

Karthikeyan Swaminathan and Ali A. Minai (2006) [39] discuss how the circle formation algorithm can be used as a means for solving other formation and organization problems in multi-robot systems. They discuss methods to make robots form different shapes like lines, semicircles, triangles and squares, and to split into groups of the specified size to perform specialized group tasks. This paper explores the use of circle formation as a generic mechanism integrating both leader-election and subsequent group assignment. But the problem with this paper is that it uses leader-election concept in which failure of leader leads to undesirable situation and secondly they have not presented the work of robustness for their algorithm i.e. they haven't discussed about what happens if a fault occurs in any of multi-robots, how they going to handle that situation is missing in their work.

X. Li and L. E. Parker (2007) [47] presented a sensor analysis based fault detection approach (which we call SAFDetection) that is used to monitor tightly-coupled multi-robot team tasks.

Flocchini, Prencipe, Santoro, Widmayer (2008) [28] explored similar model as Suzuki but in limited visibility case in detail. They showed that the robots must form a defined pattern even in asynchronous case, provided they had a sense of direction orientation (possessed a compass) also had a global knowledge of the pattern to be formed, also, in this paper it is considered that each robot of the swarm has a global view (global coordinate system) of the rest of the swarm, knowing at all times where the other members that make up the swarm are located. Fault tolerance is not the matter of interest in this paper.

Christensen, A.L., O'Grady, R. and Dorigo, M. (2008) [48] took inspiration from the synchronized flashing behaviour observed in some species of fireflies. This paper derived completely distributed algorithm to detect non-operational individuals in a multi-robot system. Each robot flashes by lighting up its onboard LEDs and neighbouring robots are driven to flash in synchrony. Since robots that are suffering catastrophic failures do not flash periodically, they can be detected by operational robots.

Ross Mead and Jerry B. Weinberg (2008) [44], presented a distributed, reactive cellular automata based formation control architecture capable of controlling any number of robots in the formation at once. Then later Ross Mead, Rob Long, and Jerry B. Weinberg (2009) [45] examined the above architecture with respect to necessary characteristics to handle real-world occurrences. To address issues of formation repair in event of robot failure and obstacle avoidance, the control architecture is extended by a distributed auctioning method that allows the robot formation to reconfigure autonomously. An important aspect of this approach is that the robots are cells in a *robot-space cellular automaton* rather than a *world-space cellular automaton.* The latter assumes that the space in which the robots exist is topologically segmented into a grid of cells.

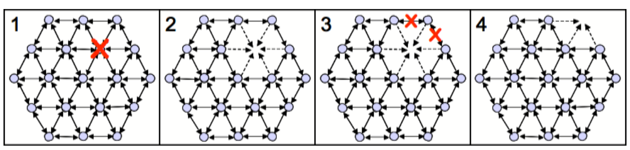


Figure 1. : The formation repair process: (1) robot malfunctions and is lost, (2) the position is auctioned, (3) a cell wins the auction and breaks its current relations, (4) the winner takes the position.

Ryan O. Abel, Soura Dasgupta and Jon G. Kuhl (2011) [11] presented geometric topology for the agent formation, and by correctly choosing the cost function, show that their algorithm produces a communication topology mirroring the geometric topology. By providing some redundancy in the formation topology it is possible for the system to survive the loss of an agent.

Bjerknes, J. D. and Winfield, A. F. (2013) [43] challenges the common assumption that swarm robotic systems are robust and scalable by default. They presented an analysis based on both reliability modelling and experimental trials of a case study swarm performing teamwork, in which failures are deliberately induced. Their case study represented a swarm task in which the overall desired system behaviour is an emergent property of the interactions between robots, in order that they can assess the fault tolerance of a self-organising system. Their findings show that in the presence of worst-case partially failed robots the overall system reliability quickly falls with increasing swarm size. They concluded that future large-scale swarm systems will need a new approach to achieving high levels of fault tolerance.
Goswami, Saha, Pal, Jana and Das (2014) [46] proposed a simple but elegant method to form an elementary geometric structure with the multi-agent system. This method is partly inspired from a foraging dynamics where the agents communicate with each other to accomplish a common goal. Only simple geometric structures like a straight line, ellipse, circle and square have been considered. The tracking ability has also been demonstrated point moving along a straight line or around a circle and surrounding it with agents in the desired shape. But this has not discussed fault tolerance capability of the system, in case, if a fault occurs.

C. Maheshwari (2014) [31] solves the minimum perimeter circle formation problem with a set of anonymous, oblivious, transparent fat-robots in a synchronized setting using SEC method. But it has many loopholes. The first problem is that this approach uses SEC for circle formation which is complicated to perform by robots. The second problem is it first make a non-uniform circle then make uniform circle not directly making it. Third, this algorithm solves the problem if one robot gets faulty but not more than that. Fourth, the robot moves only in anti-clockwise direction only not in both directions.Pilar, Fidel, and Mireia (2016) [32] presented an algorithm that, from random positions, gathers all the agents in an established geometric formation. This algorithm is partially fault tolerant because although a robot does not reach the perimeter, the rest of the swarm is able to achieve the established geometric shape. So that the partial loss of an individual does not imply any problem in achieving the final goal. But the major problem with this algorithm is that it is not completely fault tolerant, because when a fault occurs during some formed patter, it does not answer the question that what happens if a robot fails after forming the desired pattern i.e. whether the formed pattern will remain same, or change or destroy?

By studying the various papers [14],[16],[17] on fault tolerance in swarm robots or in autonomous mobile robots, it has been analyzed that there are various fault tolerance techniques that can be used as per the fault types i.e. different techniques are used for different types of faults occurred in swarm robots, which very difficult to work with. If any fault occurs in the robots, they will not function properly. So instead of using different techniques for different faults, a single common approach can be used to tolerate the fault(s). Area of fault tolerance in pattern formation of swarm robots is less explored and as a result, to handle faults in the pattern of swarm robots, very less number of an algorithm are available, one of them is auctioning method.

III. PROBLEM STATEMENT

After studying various papers on pattern formation, it has been analyzed that the most pattern formation algorithms for robots are based on smallest enclosing circle (SEC) method which is a complex method to implement. Also, the problem with most of the previous algorithm of circle formation is that first robot makes a non-uniform circle and then using the second algorithm it will form uniform circle. But we will try to propose an algorithm in which robots will directly form a uniform circle. And the major problem with these various Pattern formation algorithms is that they are not fault tolerant (or reliable). Swarm can form different geometric patterns (polygons) such as circle, square, triangle, arc etc. If a fault occurs in any of the robots in the specific formed pattern, it is difficult to handle the fault and maintain the formed pattern. These previous papers on pattern formation algorithms do not answer the question of "What happens if a robot fails after forming the desired pattern, the formed pattern will remain same or change or destroy?" In previous work, different techniques are used to handle different types of faults occurred in the swarm robots. Instead of using different techniques for different types of faults occurred in swarm robots, a single common approach can be used to tolerate any type of fault(s). This paper proposed a generic fault tolerance model to handle all type of faults in different geometric patterns of swarm agents.

IV. SOLUTION METHODOLOGY

The Models and Assumptions: Consequently, the models adopted in the previous studies assume the robots to be relatively weak and simple. Specifically, these robots are generally assumed to be dimensionless, oblivious, anonymous and with no common coordinate system, orientation or scale, and no explicit communication. Each robot operates in simple "look-compute-move" cycles. Each of the robots executes the same instructions in all the computational cycles.The basic model studied vary in two attributes. The first is Timing Models which have three types: 1) Fully-synchronous model,2) Semi-synchronous model, 3) Asynchronous model. The second attribute is Orientation Models, referring to the local views of the robots in terms of their x-y coordinates. Elaborating on [3], the following five sub-models of common orientation levels are: 1) Full-compass, 2) Half-compass, 3) Direction-only, 4) Axes-only, 5) No-compass. The models considered in this project are: **Asynchronous Timing Model:** Robots operate on independent cycles of variable lengths. They do not share any common clock. **No-compass Orientation Model:** There are no common axes, direction or orientation. Robots have their own coordinate system.Some Assumptions of this paper:

To achieve the proposed model following Methodology i.e. Models and Assumptions are considered:

- Robots considered here are relatively weak and simple. Specifically, these robots are generally assumed to be dimensionless, oblivious (Memoryless) and anonymous and with the common coordinate system, orientation or scale, and no explicit communication
- Robots follow the basic *Look-Compute-Move model.* A computational cycle is defined to be a sequence of "look", "compute" and "move" steps.
- The models considered here are as follows:
- Fully-synchronous model: The robots are driven by an identical clock, operate according to the same cycles and are active in every cycle.
- Full-compass: Directions and orientations of both axes are common to all robots.
- The robots can have two states: *active and sleep*
- Robots have Unlimited Visibility Range so that they can search the victim in less time. This can be equipped with omni-directional camera.
- Each robot has a fixed sensing range (communication range) with equipped IR sensor.
- Robots can detect and communicate with each other if they are in the limit of the sensing range of robot otherwise they will be unable to detect and communicate with each other.
- Robots are equipped with a compass that tells them direction & orientation.
- Robots do local communication with the help of wireless omni-directional camera to loacate other robots.

V. PROPOSED WORK

Many papers have been published for pattern formation. In which many researchers showed their interest in a circle formation. This is because a circle is a very simple and perfectly symmetric geometric pattern, which is why its formation is easy with oblivious and anonymous robots. The formation of other shapes is not so easy because they require designated vertices, orientations, etc. However, the ability to form circle can be exploited to form other geometric patterns. In previous papers of circle formation algorithm, the most widely used method is the Smallest Enclosing Circle (SEC) method to form the circle of robots. But this method is very complicated to be implemented by the robots and also in none of the papers it is stated that how the SEC can be practically determined in real time. The idea behind this proposed work is circle formation. Circle formation algorithm can be used as means for solving other formation and organization problems in multi-robot systems. The point is Circle formation can be seen as a method of organizing the robots in a regular polygon, exploiting different geometric patterns like circle square, triangle, etc. The algorithm that achieves these tasks are entirely distributed and do not need any manual intervention. The main work of this paper includes and extends the robustness and reliability of this model by simply making it fault tolerant. Fault tolerance in geometric pattern formation can be achieved by considering and implementing the mathematical properties of a circle and developing a generic fault tolerance model.

A. Fault Tolerance Model

In rescue and surveillance tasks with autonomous robots, it is interesting to position a swarm of robots around the perimeter of a given 2D shape. Our proposal places the members of the swarm on the perimeter of a regular polygon (geometric formation) depending on a number of robots. This proposed model is a distributed (all robots have the same information), scalable (the system should be able to operate under a wide range of group sizes), robust and fault tolerant algorithm (system should be able to continue to operate, despite failures in the individuals, or disturbances in the environment). The workflow of the proposed work is shown below with the help of flowchart:

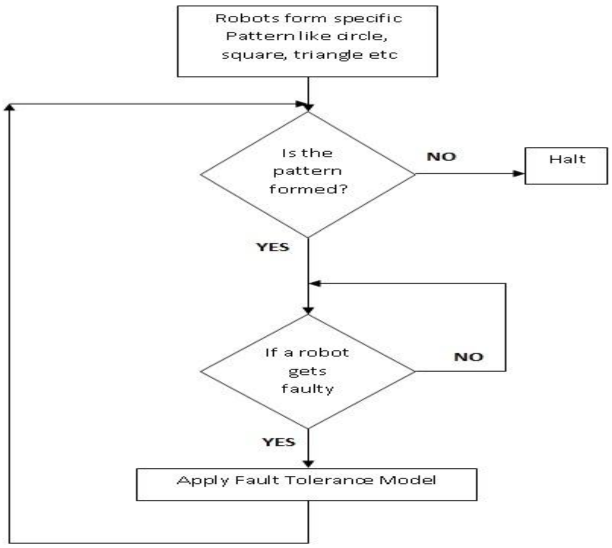
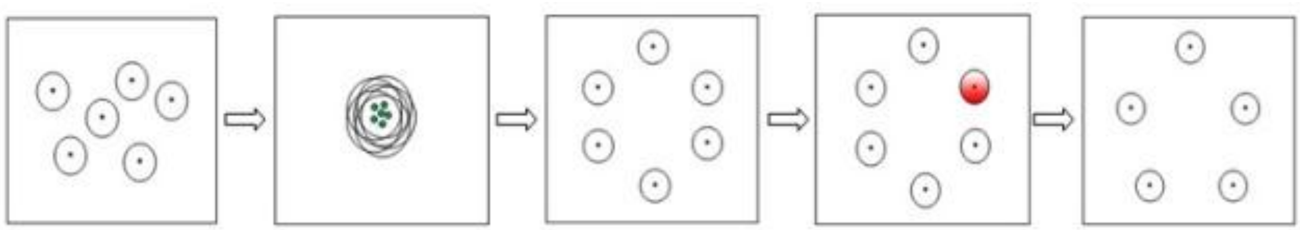


Figure 2: Design and Work Flow of Proposed approach

This proposal involves different states starting from the initial position of robots to pattern formation and then fault tolerance. The possible states are shown below in figure 3.



(a) (b) (c) (d) (e)

Figure 3: (3a) Initial Position; (3b) Gathering at Centroid; (3c) Formation of pattern; (3d) Fault occurence; (3e) Pattern restoration & fault tolerance

a) *Initial Position*: In initial position all the robots (equipped with sensor, compass, GPS) are positioned at different places, to start the process of pattern formation.
b) *Gathering at Centroid*: All robots locate each other in the arena and calculate the centroid/origin, where they have to gather or group together, by moving towards it.
c) *Formation of Pattern*: As per given radius and calculated centroid/origin, each robot calculate the perimeter of the circle
and according to that find the angular distance to be maintained between them and then form the circle (regular polygon) by moving toward the calculated location.
d) *Fault Occurrence*: Any robot may get faulty during the formed pattern.
e) *Pattern Restoration & Fault Tolerance*: If a fault occurs then by applying the fault tolerance model, the effect of the faulty robot in whole pattern will be handled and the pattern will be restored and hence fault will be tolerated.

B. Implementation of the model

The implementation of robots can be made possible by using Raspberry Pi2 and Arduinos. The means of communication can be made by ZigBee which forms the means of interaction. The ZigBee module is implemented in each and every robot and this forms the communication process. The motor is fixed to the wheels and this enables the locomotion of the swarm.

VI. Conclusions and Future work

This article proposes a simple but elegant method to form a geometric pattern with the multi-agent system. This model is distributed, decentralized, robust, fault tolerant and scalable for the pattern formation of agents from random positions and maintaining that pattern in case of a fault. By using this proposed approach, each robot for a specific organization task can be *pre-loaded* with a generic program whose execution by all individual robots will lead to the desired organization *without the need for manual intervention.* In future, we propose and develop the algorithm, simulation and implementation of this model.

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