An Adaptive Pattern Formation Approach for Swarm Robots

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Abstract—**This paper addresses a new adaptive algorithm for pattern formation problem in swarm robotics. The swarm performs a circle formation behavior autonomously, regardless of the size of the swarm. This algorithm enables an adaptive behavior to allow the swarm to both prevent collision and compose a specific formation of robots in particularly cluttered environments. The formation algorithm is integrated into a decentralized navigation system and tested in a 3-D robotic simulator. The results are encouraging and motivate authors' to perform further research with this algorithm.**

Keywords-swarm robots; adaptive pattern formation; navigation; circle formation

I. INTRODUCTION

An interesting trend in robotic from engineering perspective has moved to the design and use of a large number of low-cost robots with limited skills, which are however, capable of performing slightly complex tasks in a collaborative manner [1] In swarm robotics, a solution to a problem first emerges through the local collaborations between robots in the swarm, which is then followed by the interaction between the swarm and its working environment [2]. Pattern formation is also a critical and challenging research field, mainly in areas related to swarm robotics and multi-agent systems. This field essentially aims to form a complex system by evaluating interaction and cooperation between robots [3], [4]. Pattern formation behaviour allows robots to navigate in a regular manner that basically provides a specific distance between robots that creates a desired pattern [5]. Pattern formation behaviour is inspired from biology and physics such as the spatial nature of bacterial colonies and distribution of molecules respectively.

The main approach lies behind the pattern formation behaviour is to employ virtual forces to coordinate the robots [6] and generate a predefined patterns. In one of those studies, robots interact with each other using virtual springs that are used by a centre robot to calculate attractive and repulsive forces [5]. Besides, another study reveals that if some global knowledge is provided such as orientation provided by a sensor, the swarm can achieve subset of all possible patterns [4]. Comprehensive review papers were published and can be seen in corresponding reference [7]. Pattern Establishment problem can be separated into two groups, namely, Identification of robots and referencing mechanism [7]. Identification of robots is considered as an open issue that agents must recognize each other in an unknown environment while randomly navigating with the aim of establishing a single connected network [8]. The reference mechanism, on the other hand, allows robots to position themselves in relation to each other so as to form a desired pattern. In addition to these two mechanisms, collision avoidance and repositioning of robots with respect to obstacles are also critical issues that should be taken account in pattern establishment problem.

In this study, a new pattern formation algorithm is designed and developed that employs a comprehensive algorithm for identification of robots that employs a novel approach for initializing groups and allocate a leader for each group. Next, a simple but powerful referencing mechanism is proposed, allowing robots to form a geometric pattern without being connected to the size of the swarm. Virtual springs are also employed by member robots to prevent collision and also a global navigation method is utilized by each leader so as to lead the swarm to a desired goal position. Details of proposed study are outlined as follows: Section 2 addresses the development of the proposed pattern formation algorithm and the corresponding system, whereas Section 3 focuses on the implementation and evaluation of the proposed system. Finally, the study is concluded in Section 4.

II. PATTERN FORMATION ALGORITHM

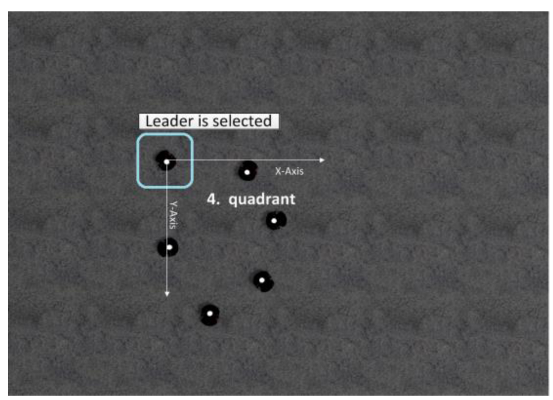

Figure 1. Grouping and leader selection behavior

Pattern formation algorithm requires grouping and leader selection behaviours respectively, which is, in essence, considered as the identification of robots phase. For this part of the study, a recent decentralized approach were adapted that is basically used for collective behaviour of multi-agent systems in a decentralized manner that includes a force based

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grouping algorithms and a dynamic leader assignment procedure [9], [10]. An example grouping and leader selection scenario is illustrated in Figures. Robots move the direction of the resultant force so as to approach each other till a certain threshold is exceeded. Afterwards, the robot which is able to detect other robots at the same quadrant is considered as the leader. The details of this part can be seen in [9], [10].

Within the algorithm, the leader robot first determines location of all member robots based on the range finder data and calculates the centre of gravity (COG) point. Afterwards, the leader draws an artificial vector $\overline{CL}$ from its position to the COG point so as to estimate the exact position of member robots (R_1 to R_n) relative to the COG point. Once the corresponding artificial vectors ($\overline{CR1}, \overline{CR2}$, …., $\overline{CRN}$) are obtained, the leader sorts member robots according to the angle they made with the COG point while considering the $\overline{CL}$ vector as the start point and moves counter-clockwise direction. The leader, on the other hand, conveys the COG point, Formation Role Number (FRN) and Number of robots to each member that allows them to move towards the possible position in the pattern regarding Equations (1) and (2).

$$pos_x = c_x + cos(\frac{360}{n} \times f) \tag{1}$$

$$pos_y = c_y + sin(\frac{360}{n} \times f) \tag{2}$$

where,
n: the number of robots,
f: the formation role number,
c: is for Center of Gravity point

Once pos_x and pos_y values are calculated with aforementioned equations, each robot moves the corresponding position within the Potential Field Method [6] in order to establish the pattern. The potential field method is employed by each robot that allows each robot to reach its position while preventing collision. The potential filed method is an efficient and powerful approach for local navigation problem. According to which, the attractive potential is calculated for the goal position, while a repulsive potential is also calculated for each of the obstacles located in the environment. Overall, the scalar potential field value 'P' can be defined as:

$$P = P_{att} + P_{rep} \tag{3}$$

where P_{att} and P_{rep} denote attractive and repulsive forces respectively. The formation algorithm is summarized as follows:

Formation Algorithm

Perform grouping and leader selection (see **[9]**)
Until the pattern formation is achieved
The leader estimates position of member robots
If positions are estimated
The leader calculates the **COG** point
Exact position of robots (**R_1 to R_n**) are calculated
The leader sorts the member robots within **COG**
COG, FRN and n parameters are passed to members
else
Try estimation again
Each member calculates its target position using **eq. (1)&(2)**
Each moves the required position using **eq. (3)**
End_Until

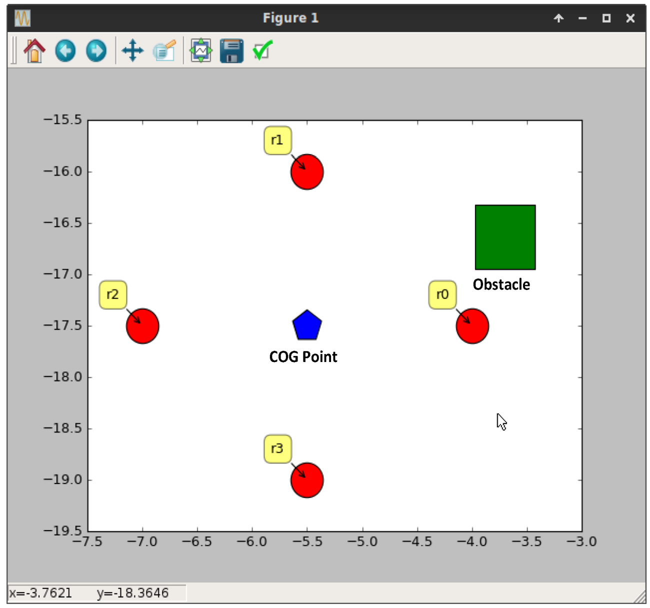

Figure 2. An example scenario, COG point is calculated and each robot tries to move its formation position (red circle)

This algorithm has adaptive characteristics, which is essential for pattern formation behavior, especially research in swarm robotics and multi-agent systems. The proposed adaptive system actually runs the aforementioned Formation Algorithm for each iteration of the navigation system.

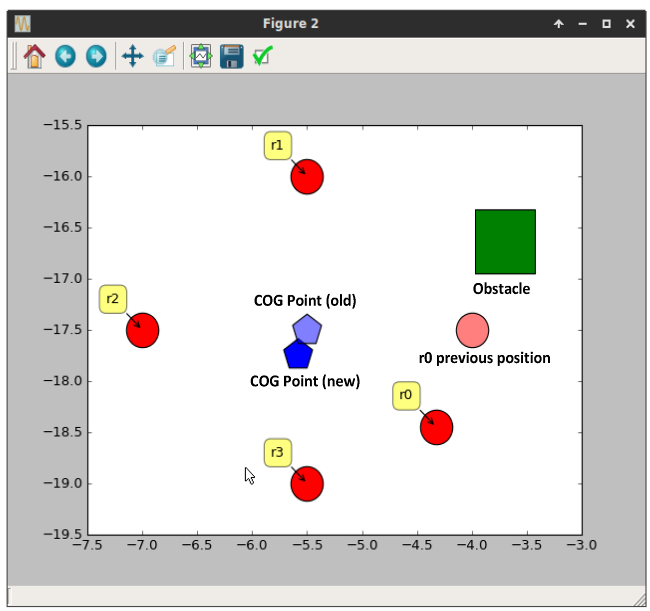

Figure 3. An example scenario, r0 avoids obstacle and it makes a sharp maneuver, also COG point is updated

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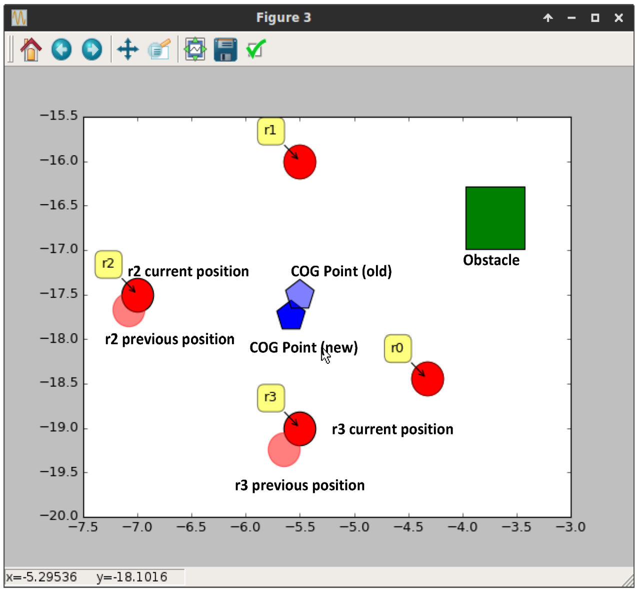

Figure 4. An example scenario, Due to the new COG point, current position of r2 and r3 are updated

That is because; as a robot, registered into the swarm, encounters an unknown obstacle, it may perform a sharp maneuver, which leads the robot from its formation role position to any other position. This maneuver both breaks the formation of the swarm and changes the COG point. Consequently, robots registered into the system must be relocated according to new COG point in an adaptive manner. An example scenario is illustrated in Figures 2-4. According to which, a swarm consists of four robots is moving towards a goal while keeping its formation (see Figure 2.) Once a robot encounters any unknown obstacle, it makes a sharp maneuver so as to avoid collision, which however breaks the formation (See Figure 3). The proposed Adaptive algorithm, on the other hand, runs the Formation Algorithm and recalculates the COG point. Accordingly, member robots are relocated according to their new position so as to form the Formation Pattern as illustrated in Figure 4. This adaptive algorithm essentially allows the swarm to keep its formation while navigating avoiding unknown obstacles.

III. Implementation of the System

This section consists of two sub-sections as follows: Implementation of the system and the Evolution of the proposed system.

A. Implementation of the System

The system is implemented using Gazebo simulator, which is already integrated with the Robot Operating System (ROS) under Linux Ubuntu (14.04) operating system. The Python language is used for configuration of simulation scenarios and for the main implementation. Screenshots from an example scenario are shown in Figures 5-8, illustrating an example formation behavior for a group of robots. At each figure, specific configuration of the pattern with respect to the time (t) is illustrated. Figure 8 illustrates the final situation that the formation is completed and the swarm starts navigating to a specific goal.

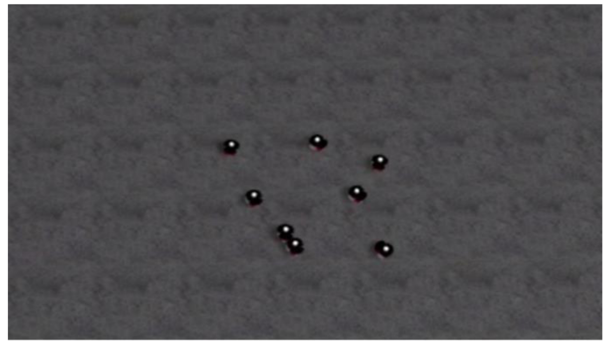

Figure 5. Grouping Scenario for 8 robots at t = 21 sec

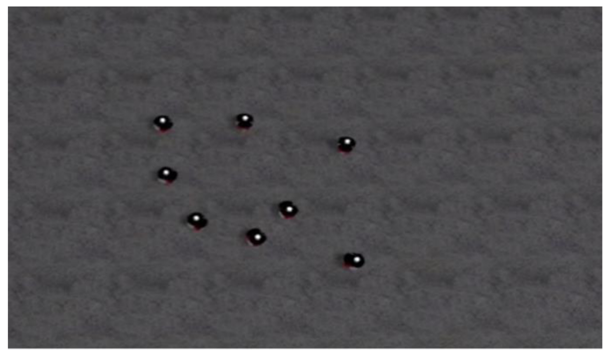

Figure 6. Grouping Scenario for 8 robots at t = 24 sec

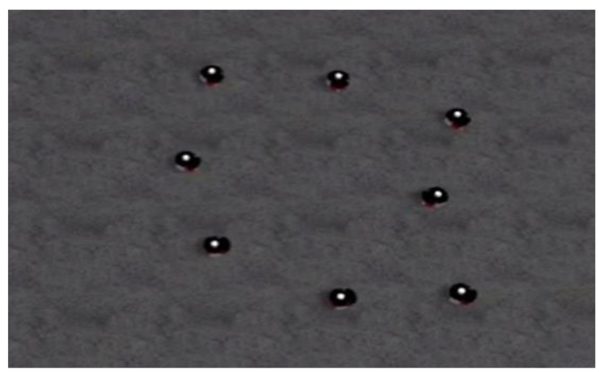

Figure 7. Grouping Scenario for 8 robots at t = 31 sec

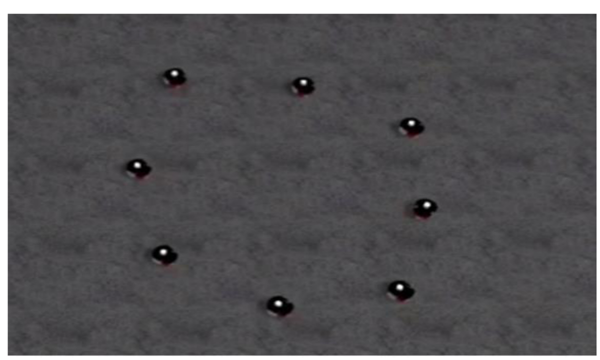

Figure 8. Grouping Scenario for 8 robots at t = 37 sec (Completed)

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B. Evaluation of the System

This section evaluates the proposed Formation Algorithm based on different performance parameters. These parameters are defined as follows:

Total formation time (t_f): This parameter shows the total duration of travel in seconds.

Total travel distance (d_t): This parameter indicates the distance travelled by the swarm from its starting position to form the Pattern.

Besides these common evaluation parameters, Swarm size (n) and Radius of the swarm (r) are also two critical parameters and considered in this section. A series of example are performed using these parameters. Figure 9 illustrates a graph which compares the t_f with n, swarm size. These two parameters are directly proportional to one other that once the size of the swarm becomes bigger, the total consumed time for pattern forming behavior increases, as it is expected.

Figure 10 illustrates the direct relation between swarm size and total travelled distance that the distance value increases with respect to swarm size and topology. In addition, radius of the pattern also increases within the swarm size, as shown in Figure 11. The minimum size of the swarm is considered as '*6'* due to the limitations of the previously defined navigation system. According to which, the system works with minimum 2 individual groups with at least 3 robots, each with one the same configuration [9].

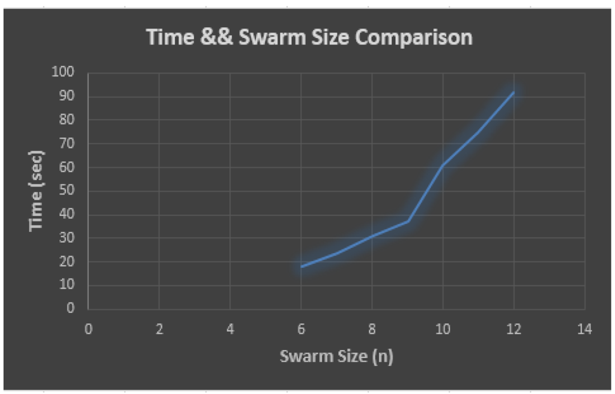

Figure 9. Evaluation of swarm size n with respect to t_f parameter

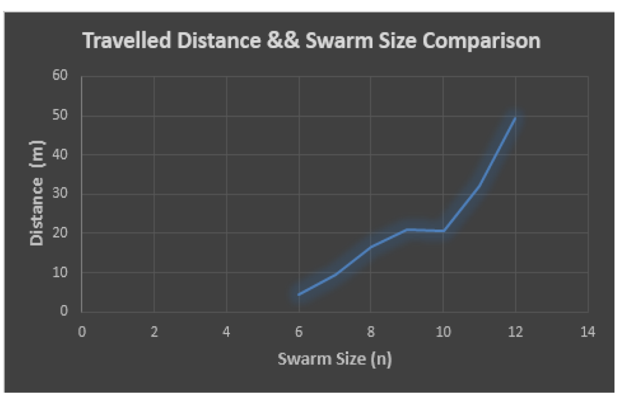

Figure 10. Evaluation of swarm size n with respect to d_t parameter

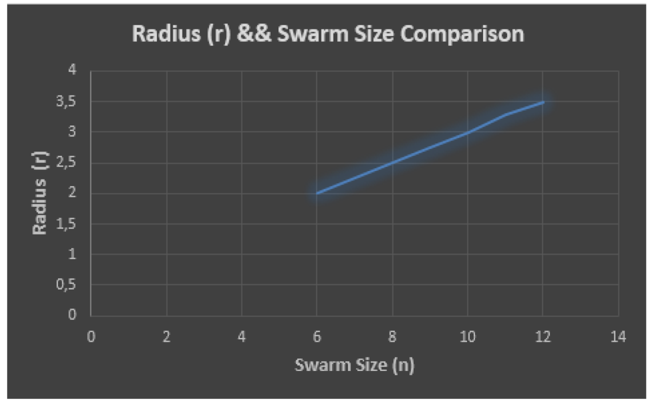

Figure 11. Evaluation of swarm size n with respect to *radius (r)* parameter

IV. CONCLUSIONS

This paper introduces a new adaptive algorithm for pattern formation problem in swarm robotics. The algorithm allows the swarm to be able to resist dynamic changes in the environment. Within the proposed algorithm, the group can generate a formation pattern regardless of the total size of the swarm. As well as, the swarm can defeat unknown obstacles and keeps composing a specific formation of robots successfully. Several experiments were performed to verify the performance the algorithm. Results reveal that the system using the proposed algorithm is accurate and efficient to navigate the swarm in a reliable manner while keeping a predefined shape (circle) in 3-D space.

ACKNOWLEDGMENT

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