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Swarm Robotics Target Searching Strategy Based on Extended Bat Algorithm

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ABSTRACT

A swarm robotics system can consists of at least two or up to hundreds or thousands number of robots. To build a system that is able to perform target searching task, it needs a robust algoritm and communication strategy. A wrong strategy can lead to unsatisfactory performance in which the swarm robots would unable to move efficiently and arrive at the target position precisely. This work aims to develop a new method for target searching strategy for swarm robotics system by adapting Extended Bat Algorithm (EBA) to the system. EBA is the low level hybrid algorithm of Bat Algorithm (BA) and Spiral Dynamic Algoruthm (SDA), and therefore its exploration and exploitation method is better than BA and SDA. EBA had proven its ability to solve general mathematical problem, however, for swarm robotics system application, its performance and effectiveness still needs to be comprehensively investigated. The investigation result shows that EBA can prove its potentiality to develop the best target searching strategy to the swarm robotics system with 5 number of iterations within 49 seconds. This is found to be the lowest number of iterations in the shortest of time. The accuracy is 99% to arrive at the desired location. Hence, the pro-posed EBA method is able to perform a target searching task for swarm robotics system.

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1. INTRODUCTION

Swarm robotics is defined as a group of robots, working together to accomplish a specific task e.g. search, surveillance. The development of swarm robotics has been inspired by the survival skill of swarm animals e.g. ants, fishes, bats and bees. Teamwork, homogenous and decentralized control are the keywords for swarm robotics system which differentiates the system from single robot, multi-agent system and multi-robot system (Miao *et al.*, 2019). Researches on swarm robotics reveals that robust, flexible and scalable can be achieved without centralization of the system (Tarapore *et al.*, 2017). Robust is the ability to cope with the loss of individuals, flexible is the ability to cope with a broad spectrum of different environment and scalable is determined by the local sensing and communication (Dorigo *et al.*, 2014).

Insects and animals which live in swarm i.e. ants, bees, elephants have inspired the development of algorithm which known as swarm intelligence such as Particle Swarm Optimization, Artificial Bee Colony Optimization and Ant Colony Optimization Algorithm. The intelligences of these creatures are for survival, searching for foods and build place to live. Swarm intelligence has been adapted to optimization problem where the approach is used to solve the maximization, minimization and optimal searching problem by mimicking the process of swarm intelligence of the creatures. Adapting swarm intelligence to swarm robotics is a new approach in order to manage and develop a robust system. Several swarm intelligence algorithms that have been implemented to the swarm robotics are Particle Swarm Optimization (PSO) (de Sá *et al.*, 2016), Bat Algorithm (Suárez *et al.*, 2018) and Ant Colony Organization (Krieger *et al.*, 2000).

There are abundance of issues related to the swarm robotics such as interaction among robots and environment, task distribution, target searching and navigation control for various task such as for searching a target and exploring an area (Dadgar *et al.*, 2016; Pitonakova *et al.*, 2016). Target searching is one of the most important issues in swarm robotics. The system consists of at least two robots up to thousands of robots which can lead to chaotic scene and fail the mission if their movement are not appropriately strategized. In order to manage a group of robots, a good strategy and planning is needed to ensure the effectiveness of the robots to work as a team. The character of swarm robotics which is decentralization or leaderless make it becomes a flexible system. However, it becomes more challenging to develop a robust system as the robots need to decide their movement in teamwork behaviour.

Target searching by swarm robotics system required all the robots in the swarm to move from initial position to specific target position in a short time and with high precision. However, existing solutions are unsatisfactory as the solutions more focus to pattern formation (Peng *et al.*, 2016). Besides, the existing strategy of target searching for swarm robotics required a lot of steps to move to the exact target and use an exhaustive technique (Dadgar *et al.*, 2016). Furthermore, a few of the conventional algorithms still low in precision for the robots to arrive at the designated position (Gupta *et al.*, 2016). Consequently, a lot of time needed by the swarm robotics to complete the searching task and the successful rate of swarm robotics to carry out target searching task is low.

Based on the the aforementioned facts, thus, swarm robotics needs to have a good strategy and proper planning in order to carry out target searching task. Implementing swarm intelligence technique to swarm robotics system is one of the novel approaches as they are a lot of swarm intelligence algorithm available nowadays yet not all algorithms is suitable for all kind of applications. The compatibility, method of adapting from swarm optimization algorithm to swarm robotics is the main issues need to be figured out in the first place. Besides that, robust controller for each member in the swarm robotics is important in order to ensure the strategy and planning can be executed by the system.

2. RESEARCH METHODOLOGY

Target searching algorithm of swarm robotics system is developed by adapting swarm intelligence optimization technique, EBA to the system. The performance of the target searching strategy is going to be tested for five homogenous robots with different initial position and far apart from each other need to arrive at the same desired position. These five robots has been selected as the number of members in swarm robotics system because of five are the ideal number of robots where the behaviour of the robots in the swarm can be observed and analysed properly as demonstrated in the research by M. Masar (Masar, 2013).

There are several assumptions being made prior to the simulation of the experiment as follows:

- The robots are homogeneous.
- Only centre of mass motion is considered for the robots, that means each robot is seen as a moving point.
- The sensing and communication range of a robot has been limited only for the distance in the experiment area. However, the information of pattern, targets, and location of neighbour robot will be informed to each robot for every iteration. The communication among robots is not being explored in this research study.
- Only 5 robots will be observed and analysed.
- The noises i.e. tyre slippage, friction, analysis on heading angle and communication error between robots has been neglected during the experiments.

2.1. Extended Bat Algorithm

Extended Bat Algorithm (EBA) is a low level meta-heuristic hybridization algorithm of Bat Algorithm (BA) with Spiral Dynamic Algorithm (SDA). The hybridization of these two algorithms are known as low level because the hybrid is only involved in one part of Bat Algorithm which is the exploration part. Original Bat Algorithm is updating the position of the agent by using Equation (1) while in SDA, updating the position is by using Equation (2). However, in EBA, updating position is the combination of BA and SDA as stated in Equation (3).

$$x_i^t = x_i^{t-1} + v_i^t \quad (1)$$

$$x_i^{t+1} = rR(\theta)x_i^t - (r.R(\theta) - I_n)x^* \quad (2)$$

$$x_i^t = [rR(\theta)x_i^t - (r.R(\theta) - I_n)x^*] + v_i^t \quad (3)$$

where x is agent position, v is the velocity of the agent, r is the step rate between $x(t)$ and x^*per t, θ is the rotation rate $[-\pi,\pi]$, $R(\theta)$ is the composite rotation matrix, i is the number of agent, t is the number of iteration, I_n is the matrix identity and x^* is the position of best agent.

Bat Algorithm (BA) was developed and introduced by Xin She Yang in 2012 (Fister *et al.*, 2014; Yang, 2010). The algorithm is inspired by the echolocation behaviour of a swarms of microbats. The nature of microbats communicates by using the echolocation principle. The parameters control of BA are frequency, *f*, loudness, *A* and pulse rate, *p* which determine the position of bats (agents) in a swarm.

The equations involved in BA optimisation technique is shown in Equations (4) to (9). Equation (7) is the exploitation which is random walk for local searching.

$$f_i = f_{min} + (f_{max} - f_{min})\beta \quad (4)$$

$$v_i^t = v_i^t + (x_i^{t-1} - x^*)f_i \quad (5)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (6)$$

$$x_{new} = x_{old} + \varepsilon A^t \quad (7)$$

$$A_i^{t+1} = \alpha A_i^t \quad (8)$$

$$p_i^{t+1} = p_i^0[1 - exp(-\gamma t)] \quad (9)$$

where f is the frequency, α is the constant value $[0,1]$, β is the random vector $[0,1]$, v is the velocity of bat, x is the position of bat, ε is the random vector [-1, 1], A is the loudness, *r* is the pulse rate and γ is the constant. *i* and *t* are the number of bats and number of iterations respectively. x_{new} is the new position (solution) of agent x, x_{old} is the previous position (solution) of agent x, x^* is the best agent (solution), f_{min} is the minimum frequency and f_{max} is the maximum frequency.

In Bat Algorithm, the agents / micro-bats are generating new solution by flying randomly which is the feature of BA that can be improved. Flying randomly without any guide or direction might bring the agents away from the best solution or trap in deadlock situation where wrong solution is chosen. Thus, EBA is created to improve this issue.

To improve the original BA, Spiral Dynamic Algorithm (SDA) is introduced in this study. The equations involved in SDA optimisation technique is shown in Equations (10) and (11). Equation (10) is the exploitation which is random walk for local searching.

$$x_i^{t+1} = rR(\theta)x_i^t - (r.R(\theta) - I_n)x^*(t) \quad (10)$$

$$x^* = x_i^{t+1} \left(if\ f(x_i^{t+1}) < f(x^*)\right) \quad (11)$$

where *r* is pulse rate, $R(\theta)$ composite rotation matrix, x_i^t is the current agents at the current iteration, *i* is number of agent, *t* is the number of iteration, x^* is the position / solution of best agent and I_n is the identity matrix.

The combination of both algorithms is expected to perform well together and could improve the performance of the original BA. This is because, the performance of optimization method is depending on its ability to balance exploration and exploitation phases. By applying SDA searching method, the exploration phase of BA can be improved. The only part taken from SDA is for updating the x value, and the remaining algorithm is from BA. The algorithm of EBA is shown in pseudocode in Algorithm 1.

Before starting optimization of the objective function, the user will initialise the parameters in the EBA. Frequency, *f*, initial positions of each agents, *x*, velocities, *v*, loudness, *A* and pulse rate*, p* are defined in a search area and all these parameters are dynamical parameters which will keep being updated and change during the optimization process according to the situation. Additional for EBA, rotation matrix, *R (ϑ)* and step rate, *r (k)* which are used in SDA are initialised as well and both of the parameters are fixed along the process. The *f* and *v* are updated at time, *t* as stated in Equations (12) and (13). Equation (14) is the equation which will update the position of the agent based on *f, v* and the position of the best agents.

$$f_i = f_{min} + (f_{max} - f_{min})\beta \quad (12)$$

$$v_i^t = v_i^t + (x_i^{t-1} - x^*)f_i \quad (13)$$

$$x_i^t = \left[rM(\theta)x_i^k - (r.M(\theta) - I_n)x^*\right] + v_i^t \quad (14)$$

Before the result is updated by using Equation (13), the searching method of BA is changed from random to spiral searching technique. This is the important part which changes the searching technique from random method to spiral method. The equation is taken from spiral equation SDA.

I_n in Equation (14) is the identity matrix according to the number of problems assigned. This equation will make sure that all bats assigned will follow the spiral path according to the radius and angle rotation values given by the user. Equation (15) represents the rotation matrix in *n*-dimensional space.

$$R_{i_\ell j_\ell}(\theta) = \begin{array}{c@{}c} & \begin{array}{ccccccccccc} &&& i_\ell &&&& j_\ell &&& \end{array} \\ \begin{array}{c} \\ \\ \\ i_\ell \\ \\ \\ \\ j_\ell \\ \\ \\ \\ \end{array} & \begin{bmatrix} 1 &&&&&&&&&& \\ & \ddots &&&&&&&&& \\ && 1 &&&&&&&& \\ &&& \cos\theta &&&& -\sin\theta &&& \\ &&&& 1 &&&&&& \\ &&&&& \ddots &&&&& \\ &&&&&& 1 &&&& \\ &&& \sin\theta &&&& \cos\theta &&& \\ &&&&&&&& 1 && \\ &&&&&&&&& \ddots & \\ &&&&&&&&&& 1 \end{bmatrix} \end{array} \quad (15)$$

where i_l, $j_l \in \{1,\dots, n\}, i_l < j_l$, $(l = 1,\dots,\tau)$ and the blank elements indicate 0. Then, x* is the common centre as a best value obtained in the spiral exploration process by using Equation (6). It will be updated for every iteration like previous equation.

Next, for the exploitation part, a new solution for each bat is generated locally using random walk after being selected among the current best solutions as stated in Equation (16).

$$x_{new} = x_{old} + \varepsilon A^t \quad (16)$$

where $\varepsilon \in [-1, 1]$ is a random number between -1 and 1, while A^t is the mean loudness of all bats at every time step. The final step of BA that should be considered in EBA implementation is loudness and pulse emission that are also updated correspondingly as the iterations increase. As the loudness normally lessen once a bat has found its prey, the rate of pulse emission increases, the loudness can be chosen as any appropriate value.

$$A_i^{t+1} = \alpha A_i^t \quad (17)$$

$$p_i^{t+1} = p_i^0[1 - exp(-\gamma t)] \quad (18)$$

Algorithm 1: Pseudo code of Extended Bat Algorithm (EBA)

1. Objective function: $\boldsymbol{o(x), x = (x_1, x_2, x_3, \dots x_d)t}$
2. Initialize bat population x_i and velocity v_i; $i=1,2\dots n$
3. Define pulse frequency f_i at x_i
4. Initialize pulse rate, p_i and loudness, A_i
5. Set rotation matrix, $R(\vartheta)$ and setting rule for the step rate $r(k)$
6. While (t < maximum number of iteration)
7. Generate new solutions by adjusting frequency (Equation 4), updating velocity (Equation 5) and location (Equation 6)
8. If (rand > r_i)
9. Select solution among the best solution
10. Generate a local solution among the best solution (Equation 4)
11. End if
12. If (rand < Ai) and $f(xi) < f(x^*)$
13. Accept new solution
14. Increase r_i and reduce A_i
14. End if
15. Ranks the bats and find current best x^*, current best = centre.
16. Update the centre point (Equation 7)
17. End while

Table 1 Comparison for BA, SDA and EBA

	BA	SDA	EBA
Method of searching	Movement of agents inspired from microbat and method of searching solution is random searching.	Agents search in spiral trajectories, depend on the angle of radian	Movement inspired by microbat and searching method based on spiral trajectories.
Type of algorithm	Metaheuristics algorithm	Metaheuristics algorithm	Low level hybrid metaheuristic algorithm
Advantage	Good in exploitation	Good in exploration	Good in exploration and exploitation
Disadvantage	Easily trap in local minima	Not explore all possibilities	More hyperparameters need to tune compare than BA & SDA

where α and γ are constants. For any $0 < \alpha < 1$ and $\gamma > 0$. Lastly, the algorithm will continue the searching until meet the termination condition and in this case, until the maximum iteration achieved.

Table 1 summarized the comparison of BA, SDA and EBA. EBA is the hybridization of BA with SDA. The hybridization is performed in order to improve the performance of the original algorithm and decided based on the application of the optimization. According to 'No Free Lunch' theorem, there are no single algorithm suit to all application and improvement is necessary to get the best performance.

2.2. Target Searching of Swarm Robotics

Navigate and strategize the movement of swarm robotics is important in order to manage the localization of all robots and to ensure all the robots able to work in a team. In this research study, Extended Bat Algorithm (EBA) is used to develop target searching algorithm for swarm robotics system. The theory of BA which use loudness, frequency and pulse rate as parameters control and SDA to control the exploration and exploitation path is proposed due to the potentiality and ability to be applied to swarm robotics system.

For the development of target searching strategy of swarm robotics system, EBA is used to optimize the distance of robots for target location. The bats in the optimization as searching agents is replaced with the robots. The objective function of this target searching strategy is stated in Equation (19).

$$\mathrm{D} = \sqrt{\left(x_t - x_{cp}\right)^2 + \left(y_t - y_{cp}\right)^2} \qquad (19)$$

where x_t and y_t are x and y position of the target, respectively. While, x_{cp} and y_{cp} are x and y position of the agent, respectively.

Figure 1 shows the flowchart of the proposed method to develop target searching strategy of swarm robotics by using EBA. D is a distance from initial point to final point. Applying swarm animals inspired algorithm to swarm robotics can be regarded as inspired the navigation from animal movement and habitual action of the animal. The exploration of robots in the swarm will be controlled by loudness and frequency.

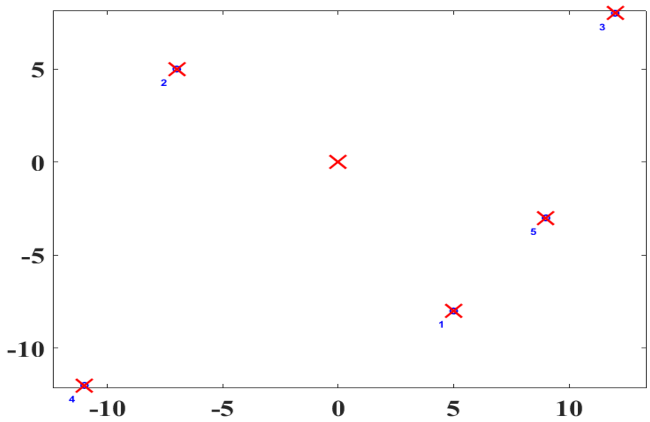

Figure 1. Initial position of robots in swarm with different distance from desired position (x: initial position of robots, bull eye: target/desired position.

Meanwhile, the exploitation of robot will be controlled by the hyperparameters of SDA which has been hybrid to BA i.e. spiral radius and spiral angle.

The main different between swarm algorithm and swarm robotics is agents in swarm algorithm will be replaced to virtual robot which the robot has physical measurement e.g. length and diameter. Thus, adaptation is important to counter the difference and make the adaptation strategy successful. If same robot goes to the same spots, in order to avoid any collision and crush during execution of the task, one of the robot will move 0.3 m from the spot. The priority to remain at the same spot will go the robot which is move from the initial spot that is closer to the desired spot. The target search task will be terminated when all the robots arrived as close as possible to the target.

Table 2 states the parameter setting used by the proposed method, EBA based target searching strategy. Five homogenous robots in swarm robotics system randomly distributed in the searching area of 30m x 30m.

Table 2 Parameters control setup for EBA

Parameter	EBA
Number of robots	5
Maximum number of iterations	50
Initial Loudness, *A*	0.5
Initial Pulse rate, *p*	0.5
Spiral Radius, *r*	0.95
Spiral Angle, θ	1
Frequency minimum, f_{min}	0
Frequency maximum, f_{max}	2.0

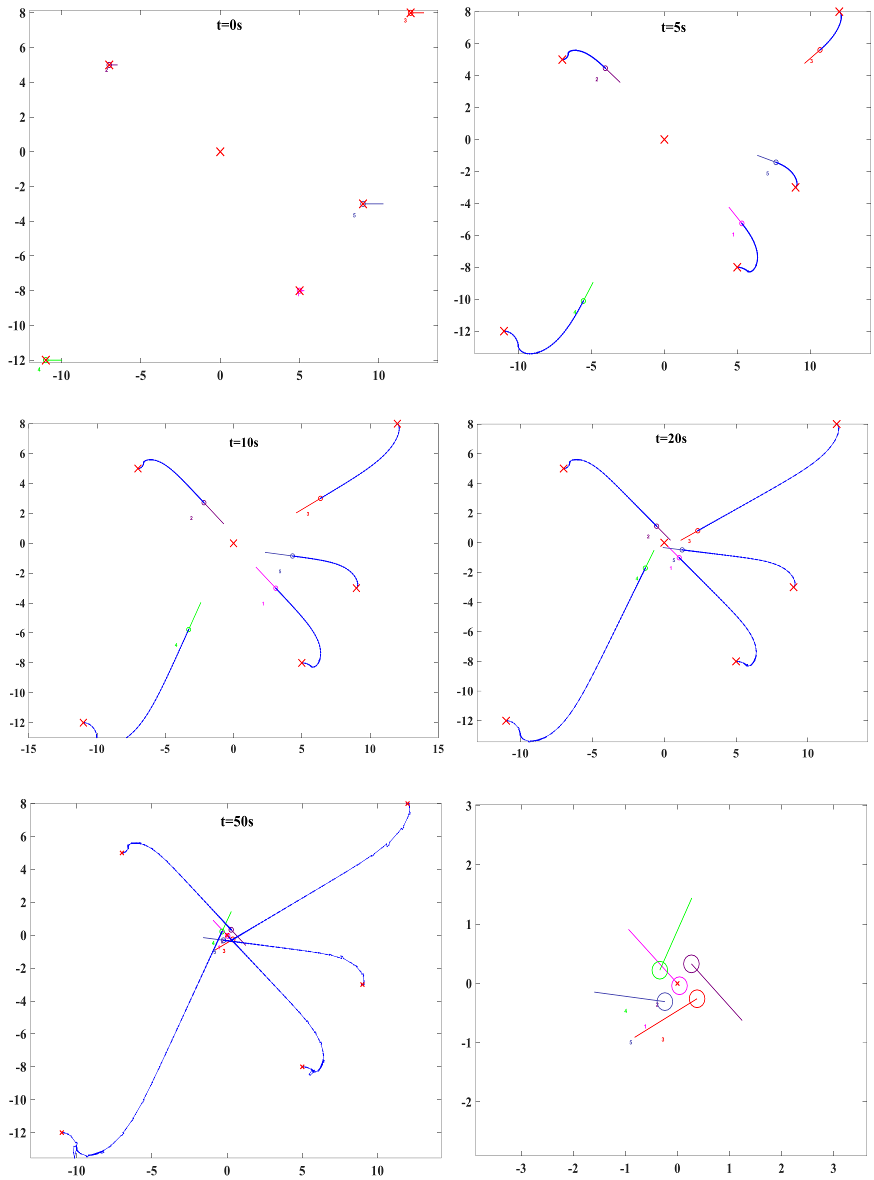

Figure 2. Trajectories for five WMR robots with PD controller in swarm robotics system perform a navigation control based on EBA (a) t = 0s, initial position (b) t = 5s, (c) t = 10s, (d) t = 20s, (e) t = 50s, (f) final position of 50s (2X zoom)

3. RESULT AND DISCUSSION

This experiment is conducted to test the ability of EBA to develop target searching strategy for swarm robotics system. Swarm robotics system for this study consist of 5 robots. A task for this research study is to move from different initial position to the same desired position. Swarm robotics usually applicable for search and rescue mission. Thus, by starting from different location is one of the strategies to avoid any blocked path along the journey to arrive at the rescue location. **Figure 2** shows the initial position of all robots in the swarm robotics system. **Table 3** states the initial position, desired position the robots need to move and distance of initial position of robot with desired location. It showed that all the robots have different distance.

Table 4 shows the result for a swarm of robots from different initial position arrived at the desired position. The desired position is set to coordinate (0, 0). Safe distance is applying in this target searching strategy where each robot has to maintain a certain distance (0.3 m from each other) so that it aware with each other and no collision between robots will occur. The experiment is repeated for five times to check the consistency of the result.

The result for number of iterations the algorithms requires to keep running the algorithm in order to achieve the target position is shows in the **Table 4** as well. The smaller number of iterations, the better the result as the target searching strategy only needs small movement to reach to the desired position. The highest iteration number is at the first and forth experiment with six number of iterations. The average number of iterations for all five experiments is 5 (~5.2). The maximum number of iterations is set to 50 and EBA shows it potentiality to perform target searching strategy for swarm robotics with just five iterations. EBA also achieved 99% of successful rate for 5 number of iterations. Although there are result show 100% successful rate, but the number of iteration and time taken were increase for those results. Succesful rate is the ability of the swarm robotics system to reach the desired position by using the strategy.

Figure 2 shows the path which had been passed through by each robot in the swarm robotics. Robot3 is the farthest from the desired position and Robot2 is the nearest to the desired position. In EBA algorithm, the position is updated for each iteration by referring to the robot with the best position for each iteration and the desired position which is set as the centre of spiral, x*. The best robot is determined by having the closest position to the desired position. Thus, EBA proves its potentiality to develop target searching strategy to swarm robotics application.

Safe distance is important element in this target searching strategy where the robot aware with each other. The swarm robotics try to maintain safe distance and when the first robot already arrives at the desired position which is (0, 0), the next robot is move 0.3 m from the first robots and the other robots continue the position itself as close to the desired position. Concentric formation is chosen to be followed by the robots for safe distance position at the final location as shown in **Figure 2(f)**. Each robot has its own dimension and weight need to be considered, thus by applying safe distance to the swarm robotics, it is considered realistic to the real application for future implementation.

Table 3 Initial position of all robots

Robot	Initial Position of robots	Target position	Distance (m)
Robot 1	(5,-8)		9.43
Robot 2	(-7,5)		8.60
Robot 3	(12,8)	(0,0)	14.42
Robot 4	(-11,-12)		16.29
Robot 5	(9,-3)		9.45

Although the distances of each robots are different, they are functioning to help each other to arrive at the target destination by exchanging information and update current position as they are applying EBA method in the strategy to develop the target searching strategy. So, all the robots are working together to accomplish the task to reach to the desired target location. If each robot does not work in harmony and cooperate with each other, robot with the farthest position from the target position maybe facing a problem to find the next position it should move, which then can lead to time consuming in solving the task. This is the art of state of algorithm theory for multi-agents where the searching agents are working together to solve the problem and by applying the same theory to swarm robotics, the reliable target searching strategy can be developed.

Figure 2 (a) to (f) show the trajectories of all robots for several times laps i.e. 0, 5, 10, 20 and 50 s. Although all the robots have different initial position with different distance from each other and desired location, the closest robot to the desired location didn't overtake and compete with other robot to arrive fast to the location, but the robot is functioning to update the position to other robots. The rest of the robot will measure their distance and compare with the best position robot. The beauty of multi agent optimization method is the agents work together to find the solution. By inspiring by the method and approach, swarm intelligent of bat algorithm has been chosen in this research study. SDA hybrid with EBA in order to help BA to find solution faster by avoiding select random solution.

PID controller that has been implemented in the wheeled mobile robot for each members of swarm robotic system smoother the target searching task of the system. The robots able to locate the position well and reduce the errors. For each iteration, each robot will update their position and balance the searching position so that all the robots finish the task at almost the same time as they are working together in the swarm. The adaptive of EBA to swarm robotics by all mean is to avoid any collision and crashing compare with novel BA which has been neglected the feature. Robots will aware with each other position and they will never take the same position. If the updating position is the same, the first robot arrive at that position is the one who take that position, while the other one will move 0.3 m from the position and update its position to the system. Therefore, by harmonising the algorithm by this adaptive, no collision will occur or can be avoided.

Table 4 Result of swarm robotics system target searching strategy based on EBA

Number of experiment *(run)*	Number of iteration *(i)*	Time, *t(s)*	Successful rate (%)
1st	6	66	100
2nd	5	49	99
3rd	5	57	100
4th	6	63	100
5th	5	55	99

4. CONCLUSION

A new approach using Extended Bat Algorithm (EBA) has been developed for swarm robotics system in performing the target searching task. A swarm robotics system which consist of 5 robots in the swarm with different distance from the desired position requires at least five iteration to arrive to the destination. More number of robots in the swarm with fixed area 30 m x 30 m required a greater number of iterations to accomplish the task to go to the desired position. From the investigation result, it is confirmed that the swarm robotics system can exhibit a good accuracy of 99%. The developed method can reach to 100% of accuracy, however the drawback is at the number of iteration. Further study will be conducted with physical robotics system applying the EBA startergy to analyse the potentiality to be applied to industrial application.

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REFERENCES

Dadgar, M., Jafari, S., & Hamzeh, A. (2016). A PSO-based multi-robot cooperation method for target searching in unknown environments. *Neurocomputing*, *177*, 62–74. https://doi.org/10.1016/j.neucom.2015.11.007

de Sá, A. O., Nedjah, N., & de Macedo Mourelle, L. (2016). Distributed efficient localization in swarm robotic systems using swarm intelligence algorithms. *Neurocomputing*, *172*, 322–336. https://doi.org/10.1016/j.neucom.2015.03.099

Dorigo, M., Birattari, M., & Brambilla, M. (2014). Swarm robotics. *Scholarpedia*, *9*(1), 1463. https://doi.org/10.4249/scholarpedia.1463

Fister, I., Yang, X. S., Fong, S., & Zhuang, Y. (2014). Bat algorithm: Recent advances. *CINTI 2014 - 15th IEEE International Symposium on Computational Intelligence and Informatics, Proceedings*, 163–167. https://doi.org/10.1109/CINTI.2014.7028669

Gupta, M., Saxena, D., Kumari, S., & Kaur, D. (2016). Issues and applications of swarm robotics. *International Journal of Research in Engineering, Technology and Science*, *VI*(July), 1–5.

Krieger, M. J. B., Billeter, J. B., & Keller, L. (2000). Ant-like task allocation and recruitment in cooperative robots. *Nature*, *406*(6799), 992–995. https://doi.org/10.1038/35023164

Masar, M. (2013). A biologically inspired swarm robot coordination algorithm for exploration and surveillance. *INES 2013 - IEEE 17th International Conference on Intelligent Engineering Systems, Proceedings*, 271–275. https://doi.org/10.1109/INES.2013.6632825

Miao, Z., Yu, J., Ji, J., & Zhou, J. (2019). Multi-objective region reaching control for a swarm of robots. *Automatica*, *103*, 81–87. https://doi.org/10.1016/j.automatica.2019.01.017

Peng, X., Zhang, S., & Huang, Y. (2016). Pattern formation in constrained environments: A swarm robot target trapping method. *ICARM 2016 - 2016 International Conference on Advanced Robotics and Mechatronics*, 455–460.

https://doi.org/10.1109/ICARM.2016.7606963

Pitonakova, L., Crowder, R., & Bullock, S. (2016). Information flow principles for plasticity in foraging robot swarms. *Swarm Intelligence*, *10*(1), 33–63. https://doi.org/10.1007/s11721-016-0118-1

Suárez, P., Iglesias, A., & Gálvez, A. (2018). Make Robots Be Bats : Specializing Specializing Robotic Swarms to the Bat Algorithm. *Swarm and Evolutionary Computation BASE DATA*. https://doi.org/10.1016/j.swevo.2018.01.005

Tarapore, D., Christensen, A. L., & Timmis, J. (2017). Generic, scalable and decentralized fault detection for robot swarms. *PLoS ONE*, *12*(8), 1–29. https://doi.org/10.1371/journal.pone.0182058

Yang, X. S. (2010). A new metaheuristic Bat-inspired Algorithm. *Studies in Computational Intelligence*, *284*, 65–74. https://doi.org/10.1007/978-3-642-12538-6_6