Journal of Theoretical and Applied Information Technology
31st October 2017. Vol.95. No 20

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

AN EXPANDED SQUARE PATTERN TECHNIQUE IN SWARM OF QUADCOPTERS FOR EXPLORATION ALGORITHM

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ABSTRACT

The exploration algorithm is one of the most important roles in the searching mechanism. In robotics field, the exploration algorithm deals with the implementation of the robot to enlarge the information over a particular environment. In other words, the implementation of exploration algorithm into a robot is intended to survey the situation or condition of a specific area. A variety of techniques has been developed, even the biological systems also become an inspiration to be reckoned. In this paper, we proposed a swarm-based exploration algorithm with expanded square pattern using a quadcopter to explore an unknown area. In this algorithm, the expanded square pattern is conducted by a series of distance around a fixed reference point. We simulate the swarm-based exploration algorithm with expanded square pattern using a VREP simulator. The existing exploration algorithms that have been identified are also simulated to be compared with the proposed algorithm. In order to analysed and evaluate the performance of all algorithms, the data of simulation is documented. Some comparisons are conducted such as the performance of all algorithms, the performance of a group of the quadcopter, the covered spaces and the cooperation among groups.

Keywords: *Coordinated Exploration; Path Planning; Quadcopter; Swarm Robot*

1. INTRODUCTION

Exploration is one of the most important utilities in searching activity to obtain information in the unknown environment. It is the basic role for searching activity because the exploration gives the main contribution in collecting information. For collecting information, the best result can be achieved if the exploration can be completed. It means that without completing the exploration, the result of searching activity cannot be affirmed surely. For ensuring a good exploration, there are two properties must be realized which are completeness and effectiveness in term of space and time respectively. The completeness requires the explorer to cover most of the area and the effectiveness emphasizes on the efficiency of the explorer to finish the exploration by minimum time. The searching mechanism needs the exploration technique to discover the unknown area. However, some problems may occur such as the path that must be discovered cannot be estimated by the robot. Hence, the robots cannot ensure whether they have covered the whole area or not. Therefore, the exploration should be conducted in such a way where it can cover a large area. It becomes an important factor to be considered so the completeness of exploration can be predicted. Moreover, another problem may occur while the area is too large to be covered. If the robots only explore to the same direction, they will need more time to explore another direction and avoid each other [1, 2]. In this kind of environment, a method for deployment of robots must be considered because it will affect the effectiveness of the exploration. Every robot should know their own area in which they belong to. Furthermore, in a searching mission that is conducted by a team, the coordination among members is very important for the division of tasks. It means that if every member does not know the status of other members regarding their position and condition, they might explore the same area that has been covered before by other members. In other words, the repetition that is done can waste their times. On the other hand, a space limitation in the environment is able to force the multiple robots to move together and multiple robots can also interfere with each other [2, 3]. The more robots used to accomplish the goal, the more time they need on detours in order to avoid collision with each other. Therefore, the coordination among all robots must be managed properly.

This research aims to enhance the exploration algorithm by adding some additional mechanism to the current algorithm by adding search and rescue techniques. By having the inspiration by how human do the search and techniques and include that elements in the traditional search and rescue actually will lead to the improvement of the current exploration algorithm with an optimized number of quadcopter searching at specific range. In the next section, some literature of the previous work done by researchers attempting to solve the issues of exploration algorithms in swarm robotics is reviewed in section 2. From the literature, the algorithm is proposed that takes into the consideration on how search and rescue is done by human in section 3. The simulations of the proposed algorithm are shown in section 4, before an analysis of the swarm's robustness after implementing this algorithm is discussed in section 5.

2. LITERATURE REVIEW

A multi-robot system has given some contribution in this research field. In this section, we want to look for various methods that have been done and get some ideas of existing exploration method. Most of them divide the exploration method into several stages that will be executed depending on the robot's situation and some of them have developed exploration algorithm that is inspired by a biological system.

Many researchers had published the exploration algorithm that fell into the algorithm of frontier-based exploration such as [4-7]. They created strategies based on an idea which was the robot(s) attempt to obtain as much new information as possible from the environment that was explored by going to the boundary between the area that had been explored and unexplored [8]. The random selection technique always had become an option in this problem study. However, when we implemented it in real life, the random selection might be an inefficient technique that was used. By constantly moving to the new frontiers, the robot can gain more information about the new territory and extend the map. In this algorithm, when the robot can navigate to a certain position, it means that that area is considered to be accessible for exploration. There are so many researchers have works [9-11] that related to this algorithm and some of them improvise it.

[12, 13] had shown some experiment about the exploration algorithm. In [12]'s work, a decentralized strategy for cooperative robot exploration had been developed. A simple and decentralized cooperation mechanism became the basic idea of this method. Each robot moved towards areas that appeared to be unexplored by the rest of the team on the basis of the available information. However, [13] offered a new method inspired by [12] that would be explained later.
After observing the exploration for a mobile robot, the following paragraph will lead us to see the exploration especially for flying robot such as MAV or quadcopter. Some researcher adopted the idea from mobile robot's exploration algorithm and others created their own algorithm. However, so far, a lot of researchers still implemented the idea introduced by [4] as their basic exploration movement that was combined with other techniques.

An exploration algorithm had been presented by [14, 15]. It was called SDE-based exploration algorithm that enabled MAV to explore in 3D indoor environments. So, the exploration algorithm was used to explore the free space. Here, the free space was represented by a set of virtual particle that was resampled based on its density to identify the representation of the environment. Additionally, [16] described an exploration and obstacle avoidance method design to be implemented on indoor MAV running in cluttered and confined indoor environment. Since, this paper aimed to three problems, this paper used the frontier based strategy from [4] for the basic exploration idea of the MAV, for getting waypoint, they used safe corridor method and SLAM navigation system was implemented for estimating position.

[17] proposed a heuristic algorithm for exploration priority. In this algorithm, they used UAV to test their algorithm in V-REP simulator. They said that their algorithm envisioned a new direction for online path planning based on the fact that the obstacle did not always hinder from

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

reaching a goal position rather sometimes it helped to find a goal position easily. In other words, they tried to use the obstacle to reach the goal position and invoked the obstacle to be the guidance. In this algorithm, [17] introduced for steps which were grid making to find the nearest next set position, cost estimation to restrict the movement options of UAV, obstacle search to avoid from any obstacle and moving to minimum cost point to navigate its position to the new location.

It can be seen that some problems are appeared with the exploration by a single robot. The exploration cannot be achieved for any kind of environment. Besides that, the range of exploration by the single robot is not as large as multiple robots and there is no assurance that the robot can cover the area as expected. However, some limitations can be solved by using multiple robots when they cooperate together. Some works have been done to overcome those problems that will be explained in the following paragraph.

Furthermore, [2] was inspired to develop the exploration algorithm based on cellular automata for swarm robot. They investigated this algorithm in real outdoor environment that used two quadcopters. In this approach, every robot had to have their own map which was a cellular grid. Every robot created their own map based on its sensing and they would share their information to one another to gain the information of the environment. Every change that were made are also updated. The coordination among the robots was done by using evaporated mark and robot behaviours. When a single robot had visited one area, it would put a mark on this area with virtual pheromones. For the exploration part, the robot would divide the area into the regular square cell and the robot could perform one step or stay in position in every iteration movement. When a robot visited a grid cell, the robot gave mark such as virtual pheromones into its map and direction and sent it to other robots. By doing that, the robot could share their information. However, after a robot visited that area, the other robot could visit the same area again since the first robot had moved to other grid cell and shared its own virtual pheromones. In other words, there was a chance where two robots or more discover the same area even if the time that they visited was different. It could be seen at Figure 3 in [2]'s paper. Besides that, the distribution of the swarm robot was not managed. It meant that swarm robot could move in the same direction at the same time.

After observing at those exploration algorithms, final problem lead us to [2]'s problem which is the possibility of robots to explore the same area that can waste time and the efficiency of the exploration regarding the number of robot is not proven statistically. Besides that, the distribution of the robot is not evaluated to support the performance of exploration. It is because the distribution or deployment of robots can give impact to the efficiency and effectiveness of exploration activity.

3. METHODOLOGY

In this section, the methodology of this research is explained. Firstly, the algorithm 1 shows the algorithm of swarm-based exploration algorithm that will be used in this research. Every robot determines their own direction based on cardinal point. After that, they go to the central point of square pattern to perform expanding square pattern which is introduced in [18] that is described in algorithm 2. Then, if each robot has complete their expanding square pattern, they will communicate to each other to determine the next location to be covered. For determining the next location, algorithm 3 is implemented. The mechanism of this exploration algorithm will be always running as long as the total area is not discovered completely.

Algorithm 1 Exploration

Require: *finding location coordinate*
initializing $(x,y)_{currentlocation}$
initializing length of area
initializing width of area

if $(x,y)_{currentlocation}$ **== *true then***
    $D_{direction} \leftarrow$ *(north|| east||south||west)*
    turning to $D_{direction}$
endif

for $i := (x,y)_{currentlocation} \rightarrow (x,y)_{centersquare}$ **do**
    moving forward
    updating i
endfor

repeat
    determining $(x,y)_{targetsquare}$
    turning right
    executing ***Algorithm 2***
    executing ***Algorithm 3***
    checking status

if $(x,y)_{coveredarea}$ == **false then**
executing **Algorithm 4**
else
STOP
endif
until maximum of expansion radius

Algorithm 2 Expanded Square Pattern

Require: finding location coordinate
while $(x,y)_{currentlocation} \neq (x,y)_{targetsquare}$ **do**
moving to $(x,y)_{targetsquare}$
turning 90° to left
updating $(x,y)_{currentlocation}$
$(x,y)_{targetsquare} \leftarrow (x,y)_{targetsquare} + 0.5$ meters
endwhile

Algorithm 3 Covered Area

if $(x)_{currentlocation}$ == **true** ∧ $(y)_{currentlocation}$ == **true then**
for $i := (x)_{diagonal} \rightarrow (x)_{currentlocation}$ **do**
for $j := (y)_{diagonal} \rightarrow (y)_{currentlocation}$ **do**
size[x][y] = (i,j)
endfor
endfor
endif

Algorithm 4 Next Location Planning

Obtaining $(x,y)_{currentlocation}$; $(x,y)_{centersquare}$; $(x,y)_{targetsquare}$
sending $(x,y)_{currentlocation}$; $(x,y)_{coveredarea}$
receiving $(x,y)_{partnerlocation}$; $(x,y)_{partnercoveredarea}$

$(x,y)_{middlepoint} \leftarrow$ equation 3.1

while $(x,y)_{currentlocation} \neq (x,y)_{middlepoint}$ **do**
moving to $(x,y)_{middlepoint}$
updating $(x,y)_{currentlocation}$
endwhile

if $(x,y)_{currentlocation} == (x,y)_{middlepoint}$ **then**
turning right
if $(x,y)_{centersquare} == (x,y)_{coveredarea}$ **then**
$(x,y)_{centersquare} \leftarrow (x,y)_{targetsquare} + 1.5$
$(x,y)_{targetsquare} \leftarrow$ equation 3.2 * 4
for $i := (x,y)_{currentlocation} \rightarrow (x,y)_{centersquare}$ **do**
moving forward
updating i
endfor
elseif $(x,y)_{centersquare} \neq (x,y)_{coveredarea}$ **then**
for $i := (x,y)_{currentlocation} \rightarrow (x,y)_{centersquare}$ **do**
moving forward
updating i
endfor
endif
endif

Equations

$$(x,y)_{\substack{middle\\point}} = \left(\frac{(x,y)_{\substack{current\\location}} - (x,y)_{\substack{partner\\location}}}{2}\right) + (x,y)_{\substack{partner\\location}} \quad (3.1)$$

$$range\ explore = \frac{length\ of\ area/2}{4} \quad (3.2)$$

$$(x,y)_{\substack{target\\square}} = (range\ explore * 2) + (x,y)_{\substack{current\\location}} \quad (3.3)$$

4. SIMULATIONS

For simulation purposes, a quadcopter has been designed using V-REP (Virtual Robot Experimentation Platform) that has become a model standard in robotics research and facilitate other researchers to conduct their works. We conducted three experiments that are divided into three scenarios. The first scenario, we create two quadcopters, the second scenario has four quadcopters and for the third scenario, we have eight quadcopters. For every scenario, the wide of the area is the same which is 24m×24m and the velocity of all quadcopters is 0.5 m/s.

Figure 1 shows the starting point of all quadcopters in every scenario for expanded square pattern. The starting point of expanded square pattern algorithm is fixed and determined by the user. For two quadcopters and four quadcopters, the starting point at the centre of the environment and for eight quadcopters, the first four quadcopters is placed at the centre and the other four is placed between the centre and the corner of the environment. Figure 2 and 3 shows the starting point of all quadcopters in every scenario for frontier baseline and cellular automata respectively. The starting points of both of them are placed in the bottom of the environment. It is applied for all scenarios.

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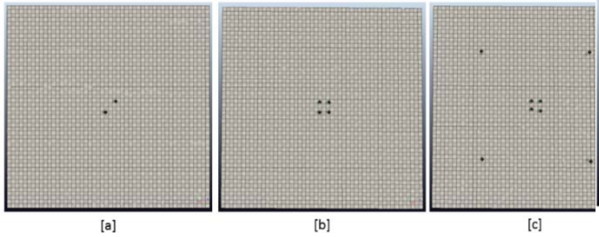


Figure 1. The Starting Point of Square Pattern Quadcopters.

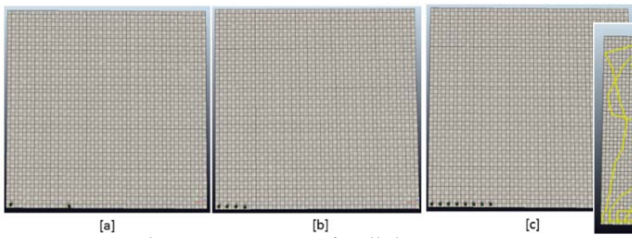


Figure 2. The Starting Point of Cellular Automata Quadcopters.

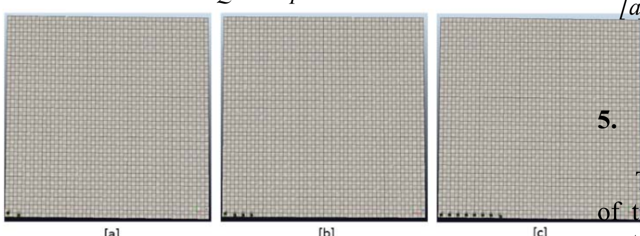


Figure 3. The Starting Point of Frontier Baseline Quadcopters.

First, we simulate the exploration algorithm with expanded square pattern, cellular automata from [2] and frontier-based approach that was introduced by [4]. In order to evaluate the performance of all exploration algorithms, the data from every simulation on a different number of quadcopters are collected and documented.

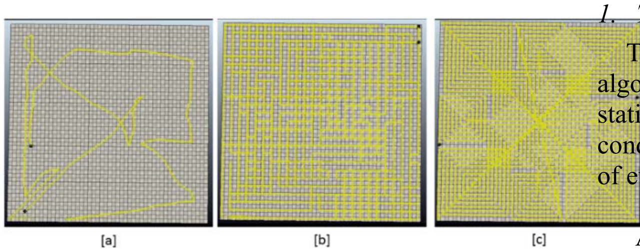


Figure 4. The Simulation Result of Two Quadcopters: [a] Cellular Automata, [b] Frontier Baseline and [c] Expanded Square Pattern.

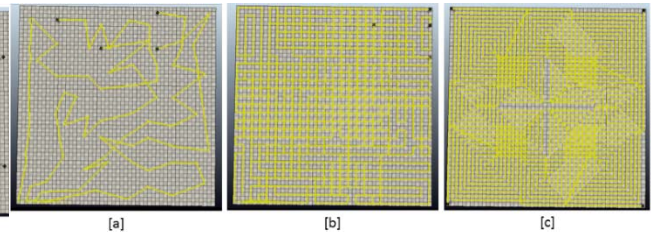


Figure 5. The Simulation Result of Four Quadcopters: [a] Cellular Automata, [b] Frontier Baseline and [c] Expanded Square Pattern.

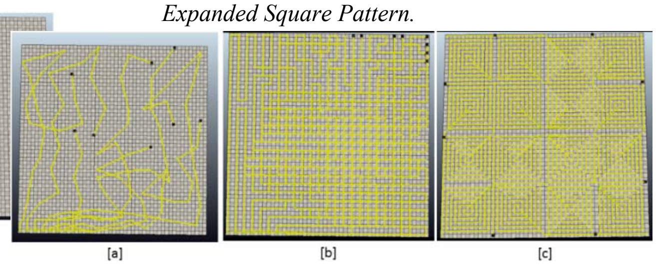


Figure 6. The Simulation Result of Eight Quadcopters: [a] Cellular Automata, [b] Frontier Baseline and [c] Expanded Square Pattern.

5. RESULTS

The simulation development has taken a period of time where start from robot simple navigation system that can only move from one point to another point. Finally, the research reaches the objective which is the development of exploration algorithm for a swarm of quadcopters that can implement the expanded square pattern to do the exploration activity. The data from different exploration algorithms are compared. The results of the comparison are analysed and evaluated. All data that have been collected is transformed into line graph in order to be observed clearly and easily.

1. The Performance of Exploration Algorithm

The performance of different exploration algorithms are presented in this section. The statistical test using Vargha-Delaney A test will be conducted to observe and quantify the performance of every algorithm.

As the proposed algorithm in this research, the result of exploration algorithm with expanded square pattern that is shown in Figure 7 gives a satisfied result. It is because the number of swarm robot that is implemented in this algorithm affect its performance.

From Figure 7, it shows that the first scenario that uses two quadcopters spend more time compared to the second and third scenario. The second scenario that implements four quadcopters

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

spends more time compared to the third scenario. In other words, it is clear that as the number of quadcopters is increased, the time that is needed for covering the whole area is decreased. For example, in scenario 1 (two quadcopters), to cover the area of 36 m^2, the quadcopters spend 1 minute and 27 seconds. If it is compared to scenario 2 (four quadcopters), for 1 minute 27 seconds, the quadcopters can cover the area of 72 m^2 and to scenario three (eight quadcopters), the quadcopters can cover the area of more than 144 m^2. The other example can be seen in the minute 05:46. Here, in the scenario 2, the quadcopters can only cover the area of 144 m^2 while in the scenario 2 and 3, the quadcopters can cover a larger area which are 288 m^2 and 576 m^2 respectively. From this point of view, it can be seen that a group of eight quadcopters is able to cover four times faster than a group of two quadcopters and a group of four quadcopters is able to cover two times faster than a group of two quadcopters.

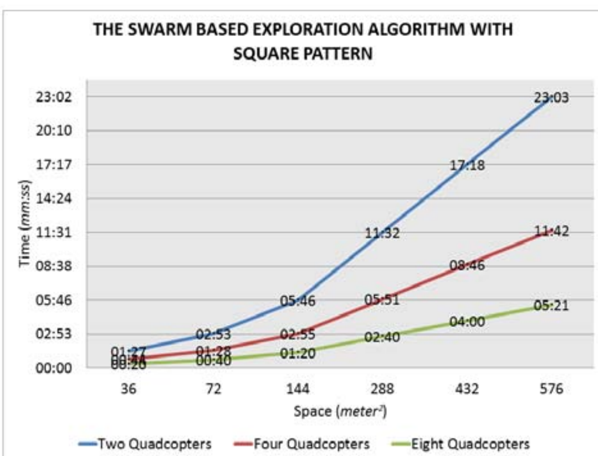


Figure 7 The Comparison Of Different Number Of Quadcopter's Performance In Exploration Algorithm With Expanded Square Pattern.

Analysing the simulation time data of proposed algorithm with expanded square pattern from two quadcopters compared with four quadcopters using the A test returned a value of 0.64. Since 0.64 is in the range of up to 64, the A test indicates a medium difference between the two data sets. The different result is gotten from the comparison of four quadcopters and eight quadcopters which is a value of 0.75 that indicates a large difference. Moreover, the result from comparison between two quadcopters and eight quadcopters gives a bigger value which is 0.86. Based on all these result, we can conclude that as the number of robot increases, the performance of swarm-robot is better.

1) *The Frontier Baseline*

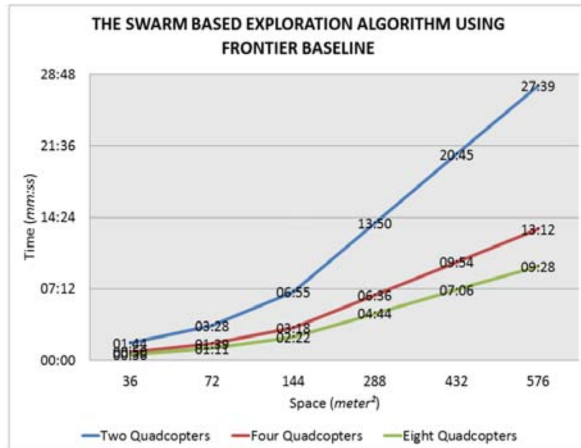


Figure 8. The Comparison Of Different Number Of Quadcopter's Performance In Exploration Algorithm Based On Frontier Based Approach.

In the experiment of frontier baseline, the similar graph pattern is also shown in Figure 8 for frontier baseline algorithm. It also can be highlighted that the number of swarm robot influences its performance. From Figure 8, it is obvious that two quadcopters need more time than four quadcopters and eight quadcopters and four quadcopters need more time than eight quadcopters to cover an area with the same size. For instance, two quadcopters explore the area of 72 m^2 and spend 3 minutes and 28 seconds. But for four and eight quadcopters, for 3 minutes and 28 seconds, they may cover more than 144 m^2. Another instance can be viewed on the thirteenth minute. At that time, two quadcopters may cover around 288 m^2 while four quadcopters almost finish their exploration and eight quadcopters has already finished their exploration. Based on this data, it can be proved that the eight quadcopters can explore faster than the four and two quadcopters which is the same result as the proposed algorithm. However, in the frontier baseline, eight quadcopters can explore only three times faster than two quadcopters wherein expanded square pattern algorithm, eight quadcopters can explore four times faster than two quadcopters.

Furthermore, analysing the simulation time data of frontier baseline algorithm from two quadcopters compared with four quadcopters using the A test returned a value of 0.75. Since 0.75 is above 0.71, the A test indicates a large difference between the two data sets. The different result is gotten from the comparison of four quadcopters and eight quadcopters which is a value of 0.61 that indicates a medium difference. Moreover, the result from the comparison between two quadcopters and eight quadcopters gives the same value as the first one which is 0.75 that indicates a large difference. Based on all these results, we can conclude that as the number of robot increases, the performance of swarm-robot is better.

2) *The Cellular Automata*

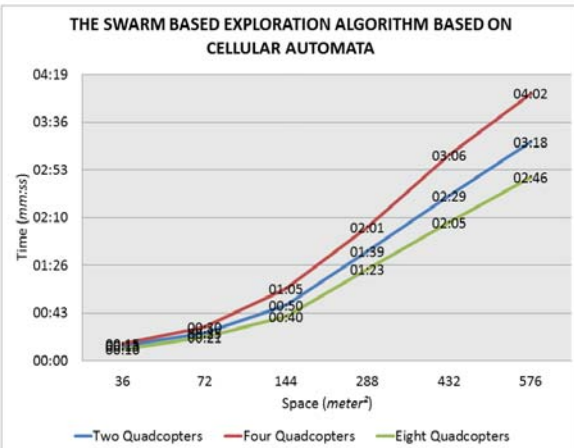


Figure 9 The Comparison Of Different Number Of Quadcopter's Performance In Exploration Algorithm Based On Cellular Automata.

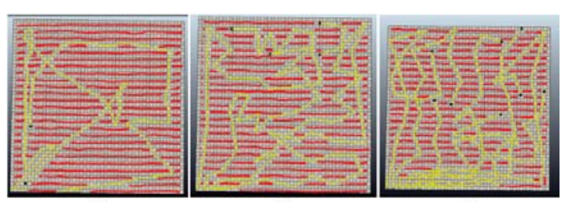
If it is compared to the other algorithms, a different arrangement is presented in Figure 9. In this line graph, a group of four quadcopters have the longest time to complete the exploration. It is followed by a group of two quadcopters and lastly a group of eight quadcopters. As shown on all algorithms, eight quadcopters always can be the fastest group. It happens also in this experiment. They only need 2 minutes and 46 seconds to cover the area of 576 m^2. However, from Figure 9, the eight quadcopters only can be two times faster than the four quadcopters which is as the slowest group. Unfortunately, if the eight quadcopter's performance of cellular automata is compared to the expanded square pattern which can be four times faster and frontier baseline which can be three times faster, the eight quadcopters of cellular automata has the lowest efficiency in its performance. Besides that, if it is seen from swarm perspective, the number of quadcopters in this algorithm as shown in Figure 9 does not affect its performance. It is proven by looking at the line graph where, although a group of four quadcopters has more quadcopters than a group of two quadcopters but it spends longer time than a group of two quadcopters to complete the exploration.

Moreover, a various result is recognized from cellular automata simulation. Analysing the simulation time data of cellular automata algorithm from two quadcopters compared with four quadcopters using the A test returned a value of 0.42. Since 0.75 is below 0.56, the A test indicates a small difference between the two data sets. The different result is gotten from the comparison of four quadcopters and eight quadcopters which is a value of 0.61 that indicates a medium difference. Moreover, the result from comparison between two quadcopters and eight quadcopters gives the value 0.58 that indicates a medium difference. Based on all these results, we can say that as the number of robot increases, it does not guarantee that the performance of swarm-robot is better.

2. The Covered Space of All Algorithms

Furthermore, in this section, the comparisons of covered space from all algorithms are exposed. The covered space is related to the time taken for completing exploration. From this comparison, it can be noticed clearly the reason of cellular automata has shorter time for its exploration.

If looking at the first comparison which is for two quadcopters (see Figure 4), it is visible that the cellular automata do not cover the whole area as it is done by frontier baseline and expanded square pattern. The same thing happens for four and eight quadcopters that can be seen in Figure 5 and 6. For the frontier baseline and expanded square pattern, they cover the whole area by exploring every pixel of the area. However, for the cellular automata, they just go around one space and move along to explore the other side of the environment. By looking at those figures, it is recognizable that the cellular automata has less explored space compared to the others although they can finish the exploration earlier than the others. In order to observe it more clearly, Figure 10 shows the uncovered space that is marked by red colour.



[a] [b] [c]

Figure 10. The Uncovered Space (Red Colour): [A] Two Quadcopters, [B] Four Quadcopters And [C] Eight Quadcopters.

3. The Cooperation among Quadcopters

Journal of Theoretical and Applied Information Technology
31st October 2017. Vol.95. No 20

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

After looking at the performance of all algorithms, evaluating the different numbers of quadcopters' performance and covered space of algorithms, the finishing time of members in every group should be observed. As far as the swarm-based algorithms concerns, those three algorithms should consider the finishing time as an important element in the swarm-based system. It means that since the swarm robot is described to have the result of collective behaviour [19] so the cooperation among quadcopters become necessary to be noticed in this context. Therefore, the cooperation among quadcopters is related to the time that quadcopters start and end their cooperation with each other.

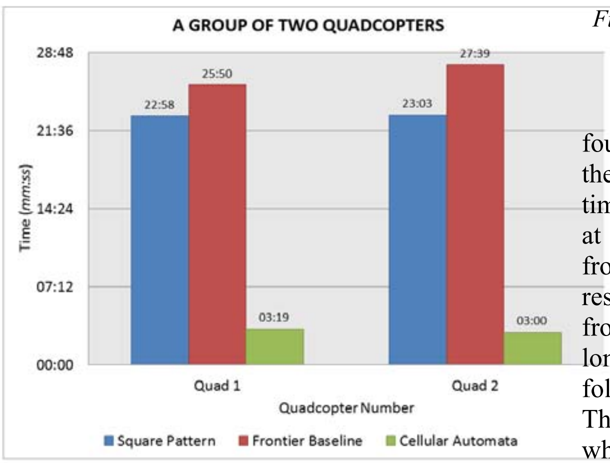


Figure 11. The Comparison Of Duration Among Group Of Two Quadcopters.

The first observation is aimed to the group of two quadcopters. Here, as shown in Figure 11, the expanded square pattern has the smallest time gap compared to the others which is only 5 seconds. It is followed by cellular automata with 19 seconds and frontier baseline with 1 minute and 49 seconds.

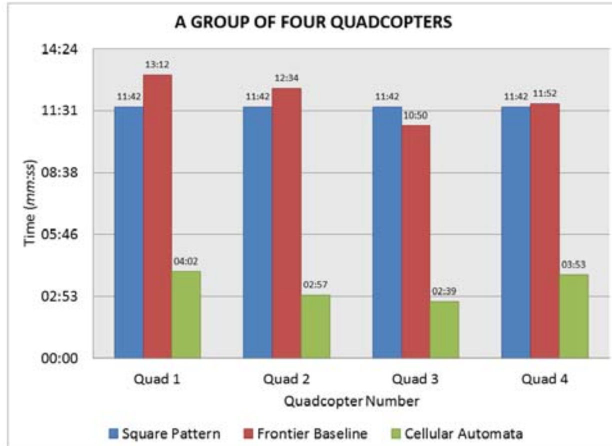


Figure 12. The Comparison Of Duration Among Group Of Four Quadcopters.

The other result is recognized from the group of four quadcopters from Figure 12. In this scenario, the expanded square pattern has a satisfied finishing time. All of its quadcopters finish their explorations at the same time which is 11:42. Nonetheless, the frontier baseline and cellular automata has various result of each their quadcopters. For example, in the frontier baseline, the first quadcopter take the longest time to finish which is 13:12 and is followed by second, fourth and third quadcopter. The same result is also shown in cellular automata where the first quadcopter takes the longest time which is 04:02 and is followed by the fourth, second and third quadcopter.

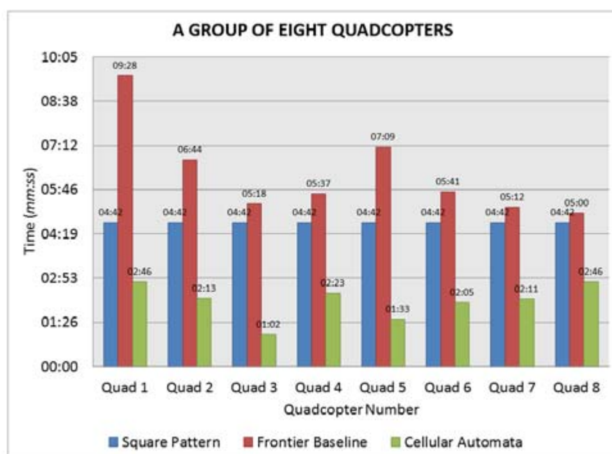


Figure 13. The Comparison Of Duration Among Group Of Eight Quadcopters.

Lastly, the result of the group of eight quadcopters is described in Figure 13. Here, the expanded square pattern's quadcopters have two different finishing time that is divided into two

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

group of time which are 04:52 and 05:21. The first four quadcopters are 04:52 and the second four quadcopters are 05:21. The time gap is 29 seconds. In the frontier baseline, every quadcopter has different finishing time. The longest time gap is 4 minutes and 28 seconds. The same thing happens for cellular automata where every quadcopter have different finishing time. The longest time is for 1 minutes and 44 seconds.

CONCLUSIONS

By implementing the expanded square pattern that is introduced by National Search and Rescue Manual, Australia in [18], we proposed a swarm-based exploration algorithm using quadcopter for an outdoor environment that can be applied in the large area. We presented the algorithm of exploration with expanded square pattern. In addition, we simulated the proposed algorithm in VREP simulator and also the swarm based exploration algorithm with cellular automata [2] and frontier baseline [4]. Based on the simulation, those three algorithms are analysed, compared and evaluated.

For the time factor, the cellular automata has the shortest time to finish the exploration and is followed by expanded square pattern and frontier baseline. However, it happens because the completeness of covered area of this algorithm is not as much as the other exploration algorithms do. Besides that, based on the Vargha-Delaney A test, the expanded square pattern has the best result compared to the others. Therefore, based on this result, it can be said that as the number of quadcopters is increased, the performance of quadcopter is better. In other words, the more quadcopters are added, the faster they can complete the exploration. In addition, we compared also the performance of each group. It showed that the effectiveness of cellular automata's performance is not good although it has the shortest duration of exploration. The completeness factor is also evaluated by comparing the space covered by every group of quadcopters. The result is derived from captured simulation and it shows that the cellular automata cover the least area compared to expanded square pattern and frontier baseline. Hence, in term of completeness of the space, the expanded square pattern has the better result than the cellular automata. Finally, as a part of cooperation concern, the expanded square pattern has the best result since most of its quadcopters start and end their exploration at the same time.

ACKNOWLEDGEMENT

This research was supported by the Malaysian Ministry of Higher Education under the Research Acculturation Grant Scheme (RAGS): RAGS 12-006-0006 and Research Initiative Grants Scheme (RIGS): RIGS16-346-0510

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