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

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

SIMULATING THE IMMUNE INSPIRED ENERGY CHARGING MECHANISM FOR SWARM ROBOTIC SYSTEMS

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ABSTRACT

Fault tolerance or the property that enables a system to continue its operation properly in the event of partial failure is one of the most desired criteria in swarm robotic systems. There is a possibility that a continuous failure of the member(s) of the swarm, will reflect on the overall performance of the systems. In this paper, we proposed an immune-inspired energy charging mechanism, which is inspired by the process of immune responses. The proposed energy charging mechanism is presented, simulated and compared with another common energy charging mechanism, which is the use of contact-less energy charging area. Based on the experimental results, the proposed mechanism shows an improvement in terms of performance time and aggregate energy of the swarm to perform its task.

Keywords: *swarm robotics, simulation*

1. INTRODUCTION

Swarm Robotics (SR) is a relatively new field of study that is inspired by social insects such as ants and bees, birds and other animals, and concerned with coordinating and controlling the behaviour and interactions of multiple small robots. It is the study of how a large number of simple agents can be designed and developed such that the desired behaviour emerges from the interactions among agents and between agents and the environment. A large number of robots involved in performing a task gives the swarm system an advantage over the more common approach of the singular robot. By having multiple robots performing the task, a failure of some members of the swarm may not reflect on the performance of the swarm, thus fault tolerance and robustness of the swarm makes it more desirable. However, continuous failure of members of the swarm due to low energy will have a large impact on the overall performance of the swarm. The collective behaviour of the swarm might be affected and cause a task not to be performed. A mechanism that allows the swarm to heal itself will improve the swarm's robustness. We propose a mechanism inspired by the ability of human body to heal itself via internal communication and coordination between the immune cells to form a granuloma. This research aims to map the components of granuloma formation into a swarm system, in order to develop an energy charging mechanism, and compare it with another mechanism. In the next section, some literature of the previous work done by researchers attempting to solve the issues of energy in swarm robotics is reviewed. From the literature, a model and a mechanism for energy charging in swarm robotics are mapped based on granuloma formation, and details of the agents involved in the charging mechanism are discussed in section 3. The simulation and results of the proposed mechanism are shown in section 4., before an analysis of the swarm's robustness after implementing this mechanism is discussed in section 5.

2. LITERATURE REVIEW

This new approach of a swarm of multiple small robots has many advantages over the more classic approaches of single robot or man-bot. One of the most important advantages of swarm robots is robustness or fault tolerance. Robustness or fault tolerance can be defined as the degree to which a system can still function in the presence of partial failures, which in the case of SR is achieved from the terminology itself [1]. Having multiple robots working on the same task simultaneously and coordinately allows the loss of some members of the

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swarm, while others continue carrying out with the task. However, the overall outcome of the task may not be the same as members of the swarm continue to fail. In the case of low energy, for example, robots will need to recharge their batteries and rejoin the swarm in performing the given task, otherwise, the task will take a longer time to be achieved, and the failing robots may become obstacles in the way of active robots. Not many research on the energy-charging problem in swarm robotics has been done. While [2] studied using the behavioural model to improve the energy of swarm robotics in foraging task, [3] focused on maintaining the energy in swarm robotics through self-maintenance. [4] suggested approaches to maintaining energy balance and homoeostasis using hardware and software mechanisms. Using these mechanisms, [4] focused on deciding the priority and recharging time at the power stations for each robot using individual and collective swarm data, such as energy level for each robot and the swarm. In a similar approach, [5] introduced a mechanism to automatically achieve a balance between foraging and resting, in order to maximise the energy level in the swarm. In other words, [5] used an adaptive mechanism where the decision to either rest in the nest or engage in foraging, is made in order to make sure that more energy is gained than lost in the search for food. While these research tried to manage the energy consumption, others proposed a hardware change that could make the swarm more energy efficient. Both [6, 7] proposed and used contact-less charging batteries and platforms to reduce time spent by the robots at the power stations, as well as the need for queuing and standing by waiting to be recharged. While [6] focused on the efficiency of using electromagnetic induction to charge robots with no contact needed with the power station, [7] designed a charging station that uses Inductive Power Transfer (IPT) to charge multiple robots at the same time, with no need for docking at a power station. In a different approach, [8] designed a movable power station that robots can attach to and charge. The movable charger or power station does not take part in performing the task as other robots, but moves in the environment and allows robots to connect and charge when they need. [8] approach focused on the hardware design of the movable power station, and the ability of multiple robots to attach to it and recharge when they need. [8] did not offer more explanation on the source of power for the movable charge, and what is the next step for the power charger after running out of power. Instead, [8] only shows that the charger is not stationary, but moving in the environment, and it has multiple conductive sides that robots can dock into. On the other hand, [9] proposed an energy-sharing algorithm inspired by immune response known as "*Granuloma Formation* ", where members of the swarm share some of their own energy with low energy robots. Drawing inspiration from immune system response, [9] proposed an algorithm in which members of the swarm are compared to immunity cells fighting pathogens such as bacteria. In that scenario, a robot with low energy is thought of as an infected cell, and other robots are immune cells surrounding the infected cell to fight the infection and not allowing it to spread. In her proposed algorithm, [9] suggested that other robots would surround the robot with low energy upon receiving a help signal initiated by the infected robot, and share some of their energy based on different methods to determine how much each robot can share. This approach of energy sharing may help robots with low energy to be recharged, but it means other members of the swarm are losing their energy at the same time, and as the number of failing robots increased, [9] found that the performance of the algorithm remained the same. Drawing inspiration from an immune response similar to what [9] used, and combined with [8] approach to making the charger find the robot in need of a charge, we studied granuloma formation and introduced a new mechanism in an attempt to solve the energy problem in swarm robots.

3. MAPPING THE MODEL OF GRANULOMA INTO SWARM SYSTEM

In order to develop a mechanism for efficient energy charging of swarm robots, which also preserves the characteristics of a swarm, i.e., collaborating and coordinating to performing tasks as a group, we looked into the collaboration among immune cells in granuloma formation to fight unknown antigen and infections. At an abstract level, we are trying to come up with a swarm that is able to heal and recharge its members in the same way the immune system does. Based on the modelling of granuloma formation developed and presented by [10] and [11], a mapping of the cells involved in the formation and swarm robots can be implemented as a potential mechanism for energy charging in swarm robotic systems that we propose and present in this section.

3.1 Using Charger-Robots

In this case, the T cells from granuloma formation help to introduce "Charger-robots". Charger-robots are part of the swarm but they do not take part in the

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

task the other robots are performing; and their main tasks are: • to standby and reside at a power station • to identify the location of the robot(s) with low energy and • recharge the robot(s) with low energy In this case, if a swarm of robots is assigned to do a task in a specific environment, such as foraging or aggregation, the charger-robots will be in a standby mode at the nearest power stations located. When one or more of the swarm robots suffer from low energy, it will send a signal of help. Charger-robots will pick up this signal, and move toward the robots requiring a recharge. Once a charger-robot responds to a recharge request, and once it had recharged the robot that requested a recharge, the charger-robot will remain in a standby mode in the arena waiting for another request, until its battery level is low, in which case it will return to the power station, and another charger-robot will take its place responding to recharge requests. In this way, the charger-robot will preserve energy by limiting the number of trips it has to make from and into the power station. A minor potential drawback for this method is the difficulty for charger-robots to find and allocate the target location where robots in need of recharging are located. The charger-robot, due to its small size compared to a large environment, may not be able to successfully locate the source of the signal or find the shortest path to reach the target location. Therefore, a possible add-on to this mechanism can be a drone or a flying robot that has a better view of the environment, and it plays the role of APCs in activating and guiding T cells in the immune system. In this case, the Antigen Presenting Cells (APC) role is implemented. The main role of APC in granuloma is to activate T cells, which will move to the infection site upon activation. At the infection site, T cells will help to activate the macrophages, which make macrophages more capable of killing antigens. To simulate the role of APC, the introduction of a specially targeted communication between flying robots and mobile robots is needed. In this scenario, when a robot experiences low energy while carrying out the task, it will send a help request. The flying robot will pick up this signal and move to locate the robot requesting help and get its coordinates. The flying robot then maps the shortest path between charger-robots at the station and the robot with low energy. Then the charger-robot will be guided to the target location with the help of the flying robot. However, the use of a flying robot or a drone is suggested as an add-on to the main mechanism of using charger-robots and can have its own set of advantages and disadvantages. For our mechanism, We will further discuss the use of charger-robots alone with no drone and keep the use of flying robots as a suggested addition to the mechanism for possible future development.

3.2 Mechanism and Agents Specifications

In order to further understand the proposed mechanism, we need to look into the details of the operations taking place to recharge a member of the swarm, and the agents involved in the process. Considering a foraging task, where the environment is divided into three distinguished parts: • a nest where the robots drop food, • a field with food to be collected by the foraging robots and • a charging station area where recharging robots will reside. For the foraging robot, in case energy reaches a critical level, and robot is in need of a recharge, the robots have to simply stop working in order to preserve the energy level they have, set their beacon or LED color to red to make it easier for a charger-robot to find it and emit a help signal that can be picked and transmitted by other members of the swarm, until the charger-robot receives it. The request for help Algorithm is shown in Algorithm 1. Once the charger-robot receives the help signal, it will send back an acknowledgement signal that will be transmitted by swarm members until it reaches the robot asking for help, where it stops sending the signal and preserve energy. The message from the robot requesting recharge simply contains an ID and battery level, while the feedback or acknowledgement from the robot contains the sender's ID and the charger-robot ID.

Algorithm 1 Robot request for recharge

> ***if the*** *energy level is low* ***then***
> *stop moving*
> ***while*** *no acknowledgement from charger-robot has*
> *been received* ***do***
> *set beacon or LED colour to red*
> *send a help signal*
> ***end while***
> ***end if***

The robot asking for recharge send their ID, so charger-robots can know and distinguish the number of robots requesting recharge. And similarly, the response message contains the ID of the robot requesting help along with the ID of the robot responding to it, in order to organise the ask-and-response process. On the other end of the operation, charger-robots are in a standby mode at all time, while they are docking at the power stations. Once a signal has been transmitted through the swarm, and it reaches a charger-robot, an acknowledgement signal will be sent in response, then the charger-robot will start navigating the environment in search for the robot with the red LED, indicating the need for a recharge. When the charger-robot arrives at the robot with the red beacon, it will set the mode to charge or recharging, where it'll introduce itself, by sending a message containing its ID, and the ID of the robot that it has received the request from. When a connection is established, the robot with low energy will dock at the charger robot and start charging. Once charging is finished, the robot will set the mode to Undock and detaches itself from the charger-robot, then the robot goes back to doing its tasks, while charger-robot will be in a standby mode waiting for the next request, as long as it has enough power to charge another robot. The algorithm for the recharger-robot is shown in Algorithm 2.

Algorithm 2 *Charger robot response to a recharge request*

Dock at the power station
standby for recharge requests
if *help signal is received* ***then***
send an acknowledgement
set the mode to UnDock
while *in unDock mode* ***do***
navigate the environment in search for a red LED
if *at the target location* ***then***
set the mode to recharge
if the *connection is established* ***then***
start recharge
else
navigate the environment in search for a red LED
end if
end if
if *recharge complete* ***then***
if *Energy levelly is enough to recharge at least one robot* ***then***
standby for recharge requests
else
Go back to the power station and Dock
end if
end if
end while
end i

4. SIMULATION AND RESULTS

In this paper, we will be simulating the proposed mechanism involving a mobile robot, and compare its performance with the same simulation ran on a swarm with contact-less charging in the specified recharging area. However, we will not be simulating the suggested role of flying robot as a guiding add-on to charger-robot and leave it as a possible future development and improvement of the mechanism.

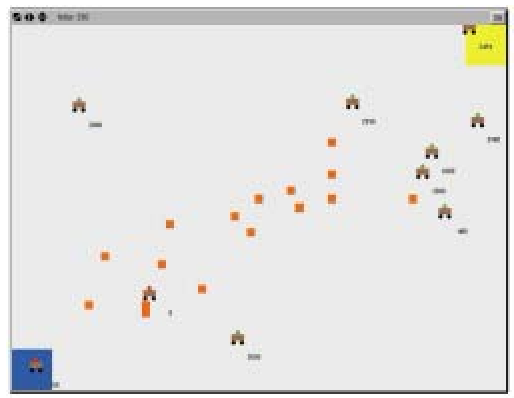

Fig. 2. One robot with 0 energy did not make it to the charging area, while another robot is already recharging it battery

In order to evaluate the performance of the proposed mechanism, the data from three simulations on different setups are collected and compared. Ten foraging robots will attempt to collect and drop 25 food items into a nest with contact-less charging and with our mechanism. The data to be collected and compared are the simulation time, number of food items collected, the number of active robots at the end of the simulation and the final aggregate energy level of the swarm

4.1 Contactless Charging Area Simulation

In this simulation, the contact-less charging mechanism explained earlier in Section 2 is implemented on the swarm. In this case, the environment is divided into nest area, recharge area and foraging area where the food is and initialized to have 10 foraging robots, 25 food items to be collected and dropped into the nest. Snapshots of the simulation are shown in the Fig. s 1 - 4. In Fig. 1 we see the environment setup with foraging robots with their energy level, food, nest area (colour yellow) and charging area (blue colour).

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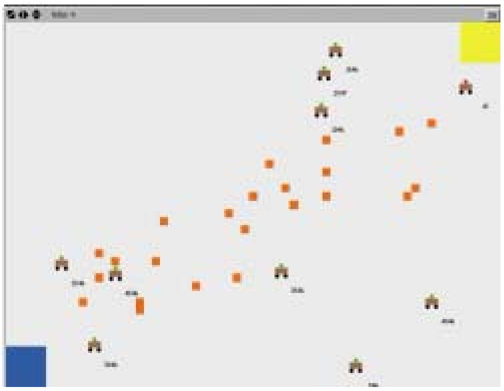

Fig. 1. Initializing The Environment With 10 Robots And 25 Food Items To Be Collected. Energy Level For Each Robot Is Showing

As the simulation progresses, robots that pick up food (yellow LED) will move to the nest to drop the food, while robots with low energy (red LED) will try to reach the charging before the battery is completely empty. As seen in Fig. 2 and 3.

Once a robot has fully charged it battery, it will set its LED colour back to green, and move out of the recharging area, and join the swarm in collecting food as seen in Fig. 3, until all food items have been collected, Fig. 4.

In order to evaluate the performance of this simulation, the data from 5 attempts on the same environment are collected and measured as shown in table 1 and the line chart in Fig. 5. From the table and the line chart it can be seen that with a recharge mechanism, the swarm will run be able to collect all food items, but at different base and with different energy level. The effect of losing members of the swarm can be seen from the table. When 43 members of the swarm ran out of energy and could not make it to the charging area for a recharge, the other 7 robots needed more time to finish the task, and the aggregate energy of the swarm was low. On the other hand, when all members of the swarm were able to recharge and collect food, the simulation ended shortly, and the aggregate energy level of the swarm was very high. The simulation time is not the same in all 5 attempts, ranging from 5934 to 8012, depending on the number of active robots.

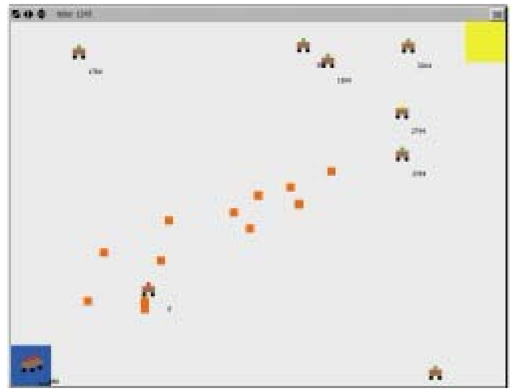

Fig. 3. Robots With Low Energy Will Move To The Charging Area, While Fully Charged Robots Go Back To Collect Food

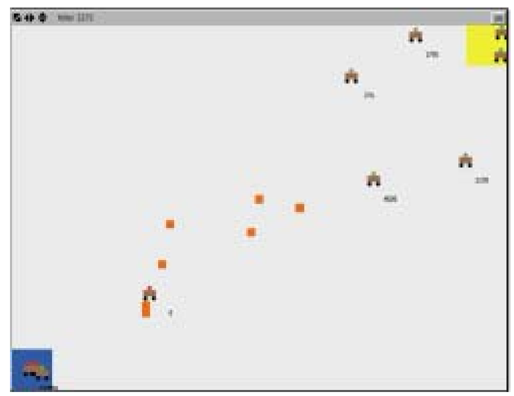

Fig. 4. The Simulation Stops When All Robots Are Dead Or All Food Items Has Been Collected

Table 1. Data Collected From Running The Foraging Simulation 5 Times With Charging Area

Simulation	Simulation Time	Food Collected	Active Robots	Aggregate Energy
1	6143	25	9	19082
2	5934	25	10	25765
3	6992	25	9	17141
4	7399	25	8	17123
5	8012	25	7	14681

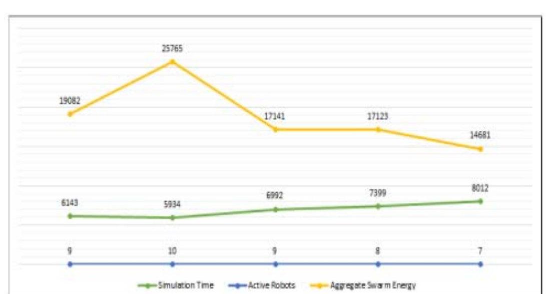

Fig. 5. Line Chart Of The Data Collected From The Simulation Showing The Number Of Active Robots, Simulation Time And Aggregate Swarm Energy

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4.2 Immune Inspired Energy Charging Simulation

This simulation is implemented on the same swarm of 10 foraging robots to collect 25 food items and using our proposed charging mechanism. In this case, the environment is divided into nest area where foraging robots will drop the food, recharge area where recharge robots are residing in wait for a recharge request and foraging area where the food is. Each foraging robot has a battery size of maximum 5000 and assigned a random value of the level of energy at the start of the simulation. On the other hand, Charger robots have a maximum battery size of 40000, meaning that each charger can fully recharge up to 8 robots. Snapshots of the simulation are shown in the Fig. 6 - 10. In Fig. 6 we see the environment setup with foraging robots with their energy level, food, nest area (colour yellow) and charging area (blue colour) where charger robots are residing.

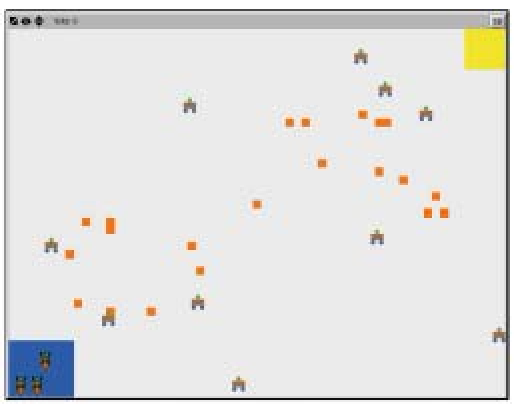

Fig. 6. Initializing The Environment With 10 Robots And 25 Food Items To Be Collected. Energy Level For Each Robot Is Showing

The simulation starts and the foraging robots move randomly in the environment searching for food. Once food has been encountered, the foraging robot will set its LED colour to yellow, and move to the nest to drop the food. When a foraging robot reaches a low level of energy, It'll stop moving and set its LED colour to red. At this point, a help signal will be issued, and a charger robot at the charging area (blue colour), we receive the signal and move to find the robot with red LED as it can be seen from Fig. 7. Once the charger robot reaches the robot asking for recharge, the recharge process starts. The charger robot will set its status to Dock, and the robot will low energy will set it status to charging. As long as the charger robot has its status set on Dock, and the robot in need of recharge is set on charging, any request from another robot for recharge will be held until the current recharge is completed. Once the recharge is complete, the charger robot sets its status to UnDock, and now can move to recharge another robot requesting help

Fig. 7. A Robot Moving To The Nest To Drop Food, While Another Is Trying To Reach The Charging Area

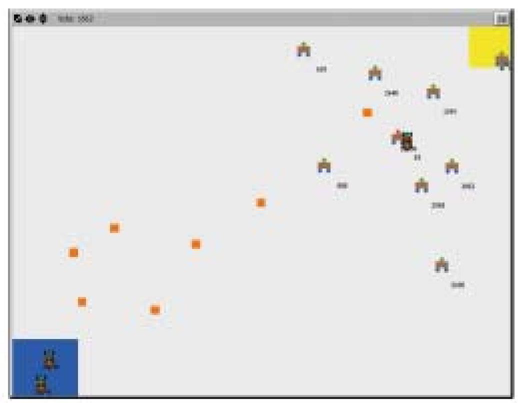

Fig. 8. More Robots With Low Energy Are Recharging, And Active Robots Are Continuing The Foraging Task As Seen In Fig. 8.

At this point, when a charger robot is dispatched out of the charging area (blue colour), and as long as it has enough battery level to fully recharge a forager robot, it will remain in the environment waiting for another request for recharge. This will ensure to save energy by not travelling back and forth between the charging area and the foraging area every time a recharging request is received. It can be seen from Fig. 9, when the charger robot receives a recharge request, and it doesn't have the sufficient energy level to carry out this task, it will move back to the charging area, and another recharging robot will take the request of recharge, and move towards the robot with red LED to recharge it. In Fig. 10, it can be seen that the simulation has stopped when all food items have been collected and dropped into the nest. The data from 5 attempts on the same environment are collected and measured, and the results are presented in Table 1 and the line chart in Fig. 11. From the table and the line chart, it can be seen that with a charger-robots mechanism in place, all 10 foraging robots were active at all time during the simulation and that all 25 food items have been collected. Having all 10 forging robots active is reflected in the simulation time and aggregate energy level of the swarm. It can be seen that the time it took to collect food items with 10 active and charged robots fluctuated between nearly 4300 and 6300, while the energy level above 25000 for 3/5 of the attempts. Taking into consideration that a full battery level for each of the 10 robots is 5000; by the time the simulation was over, an average of 50 % of the battery level for each robot was full and able to carry out with another task directly.

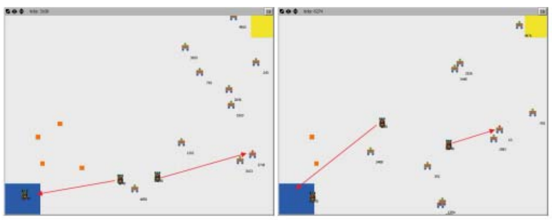

Fig. 9. Fully Charged Robot Will Set Its LED To Green, And Join The Swarm, While Other Robots Are Still Recharging

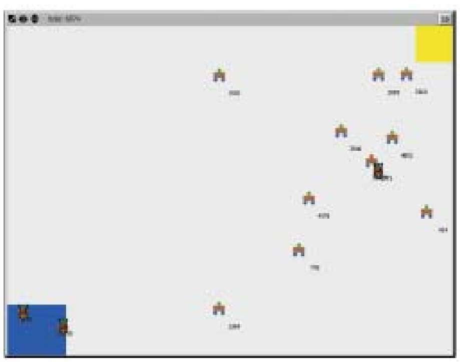

Fig. 10. The Simulation Stopped As All Food Items Have Been Collected

Table 2. Data Collected From Running The Foraging Simulation 5 Times With Charger Robots

Simulation	Simulation Time	Food Collected	Active Robots	Aggregate Energy
1	6253	25	10	24281
2	4337	25	10	28484
3	5992	25	10	23403
4	5017	25	10	26390
5	4335	25	10	25595

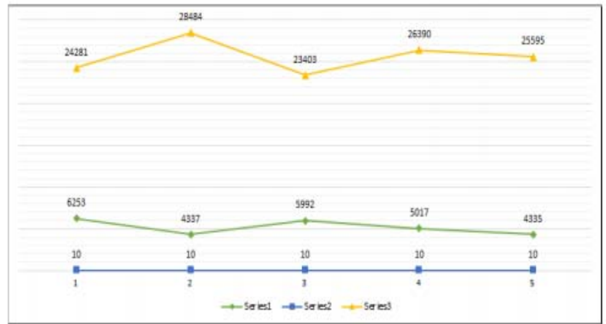

Fig. 11. Line Chart Of The Data Collected From The Simulation Showing The Number Of Active Robots, Simulation Time And Aggregate Swarm Energy.

5. ROBUSTNESS ANALYSIS

Initially, for each mechanism or setup, we run each simulation 5 times for the foraging robots to attempt to gather all food items with speed, efficiency and energy observation. The collected data from each attempt for each simulation was collected; especially focusing on the number of active robots, the aggregate energy level of the swarm and simulation time. Although the initial setup of each environment and simulation was the same, there were some differences. In all scenarios and attempts, the number of foraging robots, food items and initial energy level of the swarm was the same. However, an element of randomness was present in the initial distribution and allocation of food items and foraging robots. another obvious difference between the simulations is the recharging mechanism used. While the first simulation was an implementation of contact-less charging, where robots in need of recharge had to find their way to a designated recharging area, the second simulation was an implementation of our proposed mechanism using charger robots inspired by T-Cells in granuloma formation. In obtaining this data from running each simulation 5 times, we will compare the performance of the foraging robots using charts and the VarghaDelaney A test [12]. The set up of each of the three simulations shown and discussed earlier in the previous section 4. dictates that the simulation will keep running until either all food items have been collected and dropped into the nest, or the aggregate energy level of the swarm is 0. For the simulation of using a charging area for robots, shown in subsection 4.1., and the simulation of using charge-robot, shown in subsection 4.2.; the simulation stopped when all food items were collected. However, for the first simulation, not all

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

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

robots were active and taking part in foraging. A comparison of the results and the performance of the simulations is summarised in line charts shown in Fig. 13 and Fig. 12. The line chart in Fig. 12 illustrates the relation between the number of active robots and simulation time from the simulations with charging mechanisms implemented. From the line chart in 12, where the number of active robots (orange) and simulation time (blue) are presented, we can see from Table 3 that using a charging area as a platform where robots with low energy can Dock into and recharge had a higher mean simulation time of 6896 compared to a mean of 5186 from the simulation where charger-robots were used. Using a designated area for robots to recharge has the same problem of using power station discussed earlier in section 2. Using a charging area resulted in some robots not being able to make the journey to the charge area, and running out of

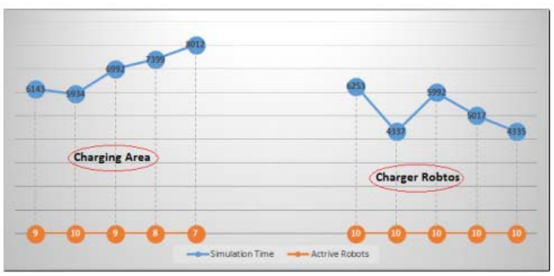

Fig. 12. Line Chart Comparing The Number Of Active Robots And The Time Needed To Collect All Food Items Collected From Simulations Using Charging Area (Left), And Charger Robots (Right)

power before being able to recharge, thereby causing the swarm to lose some of its members. The result of losing some swarm member can be seen from the line chart, where 10 active robots needed a simulation time of nearly 6000 to finish the foraging task, while 7 active robots needed a simulation time above 8000. On the other hand, having a robot in need of recharge in a standby mode waiting for the charger to come to it, resulted in a fully active swarm throughout the simulation, and less simulation time than the previous mechanism. Leading to a conclusion that *the more active robots a swarm has, the faster the simulation will finish.*

Table 3. Data Collected From Running The Foraging Simulation 5 Times With No Charge, Using Charging Area And The Use Of Charge-Robots

	No Charging	Charging Area	Charger-Robots
Avg. Active Robots	0	8.6	10
Avg. Simulation Time	4528	6896	5186.8
Avg. Aggregate Energy	0	18758.4	25630.6

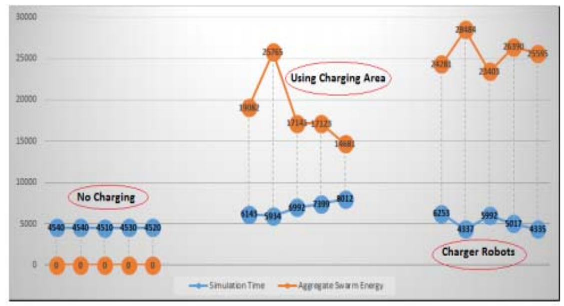

Fig. 13. Line Chart Comparing The Simulation Time And Aggregate Energy Of The Swarm Collected From 5 Simulations Using 3 Different Mechanisms, No Charging (Left), Using Charging Area (Middle) And Using Charge Robots (Right)

For the line chart in Fig. 13, simulation time (blue) and aggregate energy of the swarm (orange) from simulations are presented. To the left of the line chart, the results from the simulation with no charging mechanism in place shows that all 5 attempts took almost the same time for all robots to run out of energy. In other words, with no charging, it takes all 10 robots an average simulation time of nearly 4530 to stop moving and not being able to finish the foraging task due to low energy. As for the simulation using charging area, a rise in both the simulation time and aggregate energy level can be observed. Although the simulation time ranged from nearly 6000 to 8000, we notice that the least time it took for the foraging robots to collect all food items corresponds directly to the attempt with the highest aggregate energy level of the swarm and the highest number of active robots. Contrarily, the most time it took for foraging robots to collect all food items corresponds to the attempt with the lowest aggregate energy level and the lease number of active robots. Which leads to conclude that the faster the simulation is finished, the more efficient the swarm is in term of energy level. From the line charts in Fig. 12, 13 and Table 3, the better performance of using charging-robots can be seen. However, the question remains, to what degree can the charging robots mechanism outperform the charging area mechanism? In order to answer this question, we

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

conducted a Vargha-Delaney A test on the results from both mechanisms.

The Vargha-Delaney A test is a nonparametric effect magnitude test that can differentiate between two samples of observations [12]. The test returns a value between 0 and 1, representing the probability that one sample is better than the other. Hence, it tells you how much the two samples overlap. Values of 0.5 indicate that the medians are the same, and values of 1 and 0 mean that there is no overlap at all. Values up to 0.56 indicate a small difference; up to 0.64 indicates medium, and anything over 0.71 is a large difference. The same intervals apply below 0.5. We wrote the equations from [12] into a code in R Project and ran a statistical analysis on the data collected from the charging area mechanism and charger-robots mechanism. We employed the A test score to evaluate the difference of each simulation run. Our hypothesis for this set of experiments are as follow:

H1 Foraging robots using charging-area mechanism take more simulation time to collect all food items than charger-robots mechanism

H2 The aggregate energy level of a swarm using charger-robots is higher than using charging-area mechanism

Analysing the simulation time data from both simulations using the A Test returned a value of 0.88. Since 0.88 is above 0.71, the A test indicates a large difference between the two data sets, and that H1 is correct. Similarly, running the A Test on the aggregate energy level of the swarm yield in a value of 0.88, indicating that H2 is correct as well.

From the robustness analysis that we conducted in this section, we can conclude that the magnitude of the difference between charging area and charger-robot mechanisms in terms of simulation time and aggregate energy level was large, which means that the charger-robot mechanism results in a robust swarm system.

6. LIMITATIONS AND COMPARATIVE ANALYSIS

In comparing our proposed energy charging mechanism, we ran five simulations for our algorithm and a contact-less charging mechanism. As of the time of this work, there is no one standard or adapted mechanism for charging swarm robots, therefor there is no quantitative data to provide on the number of adapted mechanisms or the evaluation of each approach. The work in this field has been experimental so far. We compared our, algorithm with an approach that has been experimentally implemented via hardware modification of the swarm robots. On the other hand, our work has not been implemented into a swarm system yet, and hence a comparison of two working swarm mechanisms is still needed to further compare the performance and validity of each approach. It is also worth noting that our simulation setup has some elements of randomness added into it in order to account for different scenarios and situations, while such elements may not exist in the real world applications. For example, while the location of the power station is the same, we randomize the location and distribution of the food items, as well as the initial location of the robots. The effect of this randomization can be seen in the different results obtained from running the simulation five different times, while in real world, properties such as location of the robots, distance from the power stations and the energy level of the robot are pre determent and accounted, at least in the current state and use of swarm systems. It is established in our field that the real world applications of swarm systems are not yet been adopted, and most of our work is still done in labs. With that in mind, we kept our environment setup of the simulation closer to a lab setup rather than a real world with obstacles, navigation and highly dependent use of sensors. We made sure both environment are set to the same size, same location of power station and nest, and both algorithms had the same element of randomness in the swarm robots and the food elements. Comparing the results of the two algorithms, it is importance to note that both algorithms were able to collect all food items at every simulation, the difference in completing the task was observed in the number of active robots, the time needed to finish the task, and the energy level of the swarm robots. We found that our approach of immune inspired charging has a 14% higher number of active robots on average. While at the worst scenario our immune inspired approach had 30% more active robots, contactless charging was able to keep all members of its swarm active once out of every 5 simulations, meaning 20% of the time. A comparison that goes hand in hand with the number of active robots in each approach is the time needed to finish the task. Completion time for contactless charging had a minimum of nearly 6000 and a maximum of over 8000. While the immune inspired approach had a minimum simulation time of less than 4400 occurring twice, it had a maximum of 6200 once. In other words, the maximum time needed for immune inspired approach to finish the task was the minimum time needed for the contactless charging. Contactless had an average of nearly 6900 simulation time, while immune inspired had 5800, which means there is on average of 16% improvement in terms of time to perform the task using our approach. In other words, immune inspired energy charging can take 16% less time to perform a task than contactless charging. As for the aggregated energy level of the swarm robots at the end of the simulation, it can be seen from the simulation data that there was a huge difference between the two algorithms in this criteria. The immune inspired algorithm outperformed the contactless algorithm, with minimum aggregated energy for contactless at 14600 and maximum of over 25700, while immune approach had minimum of 23400 had a maximum of 28500. The average aggregated energy for the contactless charging was 18700 while for immune inspired was 25600, which is close to the maximum aggregated energy contactless charging had. In other words, the immune inspired approach for charging swarm robots resulted in over 26% more swarm energy on average.

From the comparison we can conclude that while both algorithms were able to complete the task, the immune inspired algorithm had 30% more active robots in its swarm, with 26% more aggregated energy for the swarm, and needed 16% less time to finish the task. In order to overcome the limitation of our simulation in terms of randomness elements, allocation of robots and food, and lab like environmental setup, a real world implementation of the two algorithms with working robots is needed to further confirm the comparison of the two approaches.

7. CONCLUSION AND FUTURE WORK

Swarm Robotics have properties that make them more desirable and have advantages over the classical approach to robotics. Properties such as robustness and scalability. However, in the matter of low energy, the failure of members of the swarm can reflect on the overall performance and may cause the swarm to lose its fault tolerance advantage. Inspired by an immune response known as granuloma formation, we proposed an energy charging mechanism for robots in a swarm to be recharged. We presented a model of granuloma formation in the immune system using UML diagrams and agent-based modelling simulation. Based on this simulation, we mapped the biological components of granuloma formation to the components in swarm robotic systems and proposed a mechanism that can be applied to swarm robotic systems for energy charging. In our work, we looked closely into the issue of energy charging in swarm robotic systems using aggregation and foraging simulations, then highlighted the limitations and drawback of using power stations in swarm systems. Based on a mapping of immune cells' interaction, we proposed new members of robots to be implemented for a charging mechanism. A charger-robot, equipped with a large battery, and residing at a nearby power station will come to the rescue every time it receives a signal from a robot requesting a recharge. Comparing the results of implementing the proposed mechanism with another mechanism, we found that the robustness of a swarm system can be improved, especially in terms of the number of active robots, simulation time and the aggregate level of energy in the swarm. For future work, we expect an add-on and another improvement to the proposed energy charging mechanisms to be simulated, compared and evaluated, and implemented into robots in a swarm system.

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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