On Swarming Medical Nanorobots

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Abstract

Modeling natural behaviors of swarming nanorobots is being extensively studied during the last decade. Employing these natural behaviors to nanorobots is considered highly demanded in the medical applications ranging from treating sever diseases to anti-aging treatments. Recent medical applications considers a scenario where a swarm of nanorobots is launched from a starting point into the human body to perform group tasks; these tasks could be detecting cell concentration of a specific chemicals emitted by cells and acting upon findings, or searching particular places in the human body for drug delivery or other certain actions. These applications consider scenarios that emphasize local self-coordination. Yet, these scenarios lack the global view to coordinate globally over long distances to accomplish interactively assigned group task. Considering the scenario of launching a swarm of nanorobot in blood vessel for the purpose of removing cholesterol plaques, a communication model is proposed. The model identifies communication based coordination between nanorobots in the swarm. The proposed model includes both decentralized and centralized communications for possessing both the local information within the swarm and global information for interactive task assignment, task cancellation, re-assigning new task by physicians monitoring task accomplishment. The task is simply searching lipoprotein Cholesterol threshold concentration in a specified location in blood vessel. The experimentation results has shown to be efficient as it overcomes the local minima problem for swarm navigation and problem of using coverage based particle swarm optimization.

Keywords: *Medical nanorobots, decentralized-centralized communication, swarm navigation, Adaptive Control, local maxima problem*

1. Introduction

Medical nanorobots field is becoming highly demanded in terms of ability to develop programmable and externally controllable complex machines that are built at nanoscale. A nanorobots swarm is a group of nanoscaled devices work together to perform a specific task [1]. A nanorobot swarm is a dream that became true and was inspired by the existence of nano-particles inside the human body [2]; white blood cells that roams in the blood stream around the body performing different tasks. Among these tasks: repairing damaged cells or tissues, [2, 3], repairing organs or even building new organ, [4, 5], maintaining respiration problems, repairing human vascular damage; unblocking of arteries, monitoring nutrient concentrations in the human body [6], breaking kidney stones [7]. Nevertheless, other application is considered significantly efficient for curing skin diseases, dental curing; mouthwashes to kill bacteria [8]. Recent research in the field investigates the use of nanorobots in a common scenario: exploration (navigation and detection) for the purpose of knowledge discovery, and acting upon findings certain information about the target parts of the human body. Implementing these scenarios is common for cancer detection, treatment and the diabetes diagnosis [10, 11, 12, 13].

Inspire by the motion nature of nano particles in the blood stream, the current models consider random Brownian motion for modeling the collective swarm movements' control. Accordingly, the current models use random search or signal detection of certain surface chemicals to reach the target. Signal detection based modeling approach allows the swarm members to detect chemical signals emitted by the target cells depending on chemical concentration above a threshold level using onboard nanosensors [15, 16, 17, 18]. In addition, the nanorobot has electric nanosensors to allow swarm members to detect each others as well as the signals sent to/by the medical physician. After detecting the signal, a nanorobot accelerates towards the highest concentration and starts sending attraction signal to the other swarm members [19]. These approaches can either allow high level of autonomy but lacks the interactivity with medical physician for maintaining the swarm performance: assigning new task, cancellation of a pre-assigned task, or partially discharging swarms that are far from the location. In these approaches, the interaction of nanorobot with human operator is limited to using feedback via chemical information converted into signals to receiver devices using a simple broadcast architecture [20, 21]. Then, the received signals are interpreted by the physician. Yet these scenarios lack interactivity in reassigning new tasks, cancelling old task, or extending the assigned task. This can be thought of as multicasting, broadcasting the task, or cancelling old task. In addition, ending the assigned task is also another issue to be considered in the above scenarios for the nanorobots mission [14].

Recent implementations of the above described motion nature implements decentralized algorithms for local coordination or centralized algorithms for communication with physicians. These algorithms, yet, lacks the self-coordination over long distances along with a global space view of this certain space in the nanoworld. In order to include both centralize and decentralized coordination, a swarm communication-based coordination model is required. This communication model needs to specify both local and global levels. In addition, swarm communications serve the main tasks of any swarm of nanorobots. Other main concerns when designing communications-based coordination, is that the swarm obtains enough knowledge of the swarm goals and organizational structure. This knowledge allows the nanorobots swarm to autonomously organize in order to achieve their team goal in that considers changing in environmental conditions and individual team member failures [23]. This implies that each member of the swarm needs to know how, when, what to say, and whom it communicates with. Multi-level communication models formulate the communications between multiple robots in the form of messages. Accordingly, messages are exchanged in different types. Most remarkably was the type of messages that play data transfer rule, i.e. a member of swarm does not have to reply or wait for a reply. It acts upon certain received information.

Considering the scenario of launching a swarm of nanorobot in the blood vessel for the purpose of removing cholesterol plaques from arteries, the nanorobots need to spread along the cholesterol plaque position instead of overcrowding next to a part of the plaque. The proposed communication based interactions model for a swarm of nanorobots should possess ability to coordinate in order to afford dynamic reconfiguration, adaptation, fault tolerance and survivability. Hence, the work presented in this paper proposes a methodology to adapt these requirements in order to allow the swarm to navigate towards designated target location in the space and to randomly cover almost all areas surrounding the target without losing any of the swarm members. In addition, the paper presents simulation results for extending the proposed model to nanorobotics coverage problem in a given location. The simulated nanorobot prototype model assumes the following:

1. The nanorobots has nano control design based on onboard; electrical and chemical, nano scaled sensors to help a nanorobot detecting a specified chemical concentration of the target [11, 16, 17] that has surface chemicals and allowing the nanorobots to receive electric signals from other swarm members and medical physician.
2. The nanorobot is not attacked by the white blood cells due biocompatibility [18] with the immune system reaction inside the body
3. The nanorobots moving inside the human body via flocking [1] motion inside blood arteries considering the speed of the blood stream through blood circulation system to reach the target location.

2. Methodology

For the purpose of describing the proposed model, the following scenario is considered. A swarm of nanorobots is launched in the blood vessel: navigates as a team throughout the blood flow inside the vessel. The medical physician sends electrical signal represents the threshold concentration of low density lipoprotein (LDL) to the swarm. Any swarm member can detect the LDL concentrations using chemical nanosensors; that can be programmed to detect different levels of concentrations. Upon finding the required concentration, the nanorobot could also emit signals to other swarm members to inform findings and receives responses whenever any new member reaches the specified location. The nanorobot uses the responses to determine the number of nanorobots at the target. In addition, the number of responses is used to stop emitting signals to other far nanorobots once enough nanorobots have responded. At this stage, the swarm starts performing the required action; e.g. removing the plaques from the vessel wall.

The proposed model is based on communications that allow nanorobots to communicate with each other over short and long distances to coordinate their activities. The model implements a group communication protocol in two levels. These are the local and global communications levels. The proposed method focuses on global behaviors emerges from simple individual behaviors. This is achieved by implementing the flocking algorithm as a local level for allowing swarm members to communicate over short distances along with a global level to communicate with the medical physician who multicasts the task and threshold.

Local communication level involves implementation of directed flocking algorithm as decentralized communications. This level is based on exchanging messages between nanorobots in the form of electric signals. These signals can be detected by onboard nanosensors and are representing the responses upon finding a chemical concentration equals to a predefined threshold. The concentrations are used to calculate the centroids for the flock members. The centroids control the flocking behavior and accordingly, control actions performed by the nanorobots. The nanorobots swarm members keep acting according to the sent/received signals. The flocking algorithm allows the team members to visit as many points as possible and selecting different routes which allow maximizing the covered area by their sensors.

Global communication level is used in order to centralize the communications for interactive task assignment issued by medical physician. In this context, the physician can still affect the nanorobots performance by multicasting tasks for a certain swarm. This is considered vital when the physician sends commands via external control electric or chemical signals.

This is considered as innovative approach to achieve a combination of centralized and decentralized control for a distributed collective action. Local-Global Communications provides real time flocking interactive self-coordination using four levels of control rules:

(a) Default Rule: If no other nanorobots are visible or no messages are received from medical physician move along the blood stream.

(b) Alignment Rule: This rule is also known as a velocity matching rule as each swarm member M_i tries to detect nearest member from the same team M_j and getting the velocity of this member. Hence, the M_i calculates the correction angle $\emptyset_i$ to align with the nearest member M_j. The sensory data is filtered for this rule to pick only the nearest friend, a detected neighbor from the same team. The sensor range and the field of view define the perception zone for this rule. The alignment rule results in a velocity vector an agent should follow to modify its current direction in order to align with this neighbor, if found. For member M_i, the velocity vector composes a centroid C_{Align} and a correction angle $\emptyset_i$. The centroid of this rule is considered as the distance to M_j positioned at P_i . The correction angle $\emptyset_i$ is computed as the difference between the current heading and the heading angle of the nearest member.

(c) Cohesion Rule: The cohesion rule acts as a binding force. It reinforces each swarm member to orient its velocity vector towards the centroid of the team members that fall in the field of view of this rule. For each swarm member M_i, located at corresponding positions P_i, the centroid C_{Coh} of this rule is computed as the distance to the average of the positions of the detected M_j located at P_j position. The swarm member computes the distance to the centroid C_{Coh} and a correction angle $\emptyset_i$. As a result this rule always implies the member move toward the centroids of the flock, cohere with the team.

(d) Collision Avoidance: Each rule produces a suggestion on how to decide on the next action using a set of weights to reconfigure movements. The set of weights decides the strength of relations between the swarm members. Hence, a swarm member needs to acquire some information from the others about their findings and distances from self. These are considered as local communications for local coordination.

(e) Task Assignment Rule, the physician multicasts a message to the swarm: when a nanorobot receives an electric signal from the medical physician informing the *LDL* threshold concentration and estimated position for the target cells. Each swarm member considers this as a fifth rule and calculates correction angle $\emptyset_i^{LDL}$ required to correct member direction and remaining distance to the target cells. Hence, the weight associated to this rule T_{wi} is calculated as the reciprocal of the squared distance to the target Dis_{LDLi}. When the target concentration of *LDL* is detected, the weight associated to this rule becomes higher; reciprocal of the distance to the target Dis_{LDLi} and hence the swarm member speeds up towards the goal.

The algorithm can be explained as follow: Each nanorobot as a team member:

1. Keeps moving within a team along the blood stream.

2. The physician multicast a specified *LDL* threshold concentration; hence the swarm members are interactively being assigned the task; searching a *LDL* threshold concentration.

3. As the front nanorobot in the swarm moves forward, the team centroid moves forward and accordingly all swarm members always tries to move towards team centroid.

4. The centroids are calculated including inputs from both electric and chemical nanosensors.

5. Accordingly, each swarm member calculates interactively calculates the weights using these centroids and the correction angle from each rule and then they will be combined according to the weights to produce one suggested correction angle and speed. A minimum separation distance allowed S_d between the nanorobots themselves to avoid hitting each other. Also, the collision avoidance weight is given a value greater than maximum computed weight for other two rules for each swarm member individually.

6. Once any of the swarm members detects the *LDL* threshold concentration, this member is considered a first arrival. The first arrival nanorobot uses this concentration to speed up towards the target, and sends signal to other swarm members to inform.

7. When other swarm members receive messages they speed up towards the sender, gradually reaches the target and swarm around the target location to perform the task; e.g. cutting the cholesterol plaques.

The above algorithm is being considered in simulating the two communication models: These two models are: the Global Communications (*GC Model*) and Local Global Communications (*LGC-Model*). The *LGC-Model* implements the flocking algorithm for local coordination of movements. In addition to the local communications, the LGC implements a global multicasting to allow communication between physician and the nanorobots. The *LGC-Model* implements both levels of communications and allows swarm members to communicate and move as a team. The *GC-Model* implements the global communications only. In other words the set of nanorobots moves only according to the search rule, they do not interact locally.

3. Experimentation Results

Swarm members' movements are controlled by a set correction angles and associated weights for the communication rules. These weights are: $Align_w$, , Coh_W and $Collis_W$. These weights define the perception zone for each rule through interactively calculated centroids. The weights are dynamically computed at each time interval depending on the rule's centroids. Hence these weights are seen as the filtering strategy during interactions. The experiment design addressed the following:

1. Maximizing the covered area whilst the nanorobots moving in a swarm performing sweeping tasks for the purpose of detecting high concentration defined by a threshold T.

2. Self-coordinating the swarm upon arrival to the target. The two models of communications are tested.

3. Preventing lose of swarm members during the journey
4. Grouping the swarm members into teams for the purpose of improving the self-coordination of their movements in the blood vessels and upon detecting the threshold concentration area.

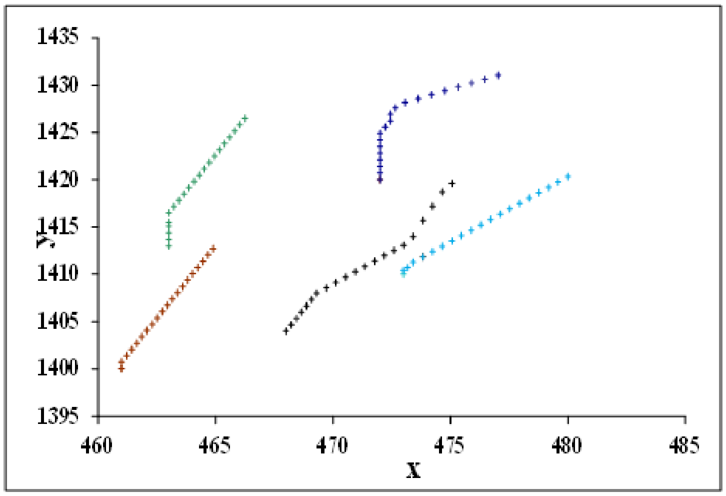

Figure 1. The Swarm Members Select Different Routes Whilst Navigating Inside the Vessel

The experimentation results presented in the following subsections show that implementing the *LGC-Model* results in superior performance in terms of maximizing the coverage areas during the sweeping task and self-coordinating the swarm members upon arrival. The experiment is considered useful in assessing and evaluating the extent to which varying the cohesion weight allows the nanorobots in the same team to move as a unit, avoid losing any member during warm navigation.

3.1 Routes and Coverage Areas

An attempt is made to explore the influence of the flocking emergent behavior on the covered area around the target. This is carried out by viewing two values, the positions of the nanorobots during movements and the area these nanorobots cover after arriving at a specified target. Therefore, the experiment aims at running the model with a set of five members forming one team. After launching the swarm in the blood vessel, Figure 1, the physician issues a team task that informs a *LDL* threshold concentration. The swarm moves forward with the blood stream, and swarm members' positions are recorded and plotted over a number of time frames. Figure 1 illustrates swarm members positions whilst moving within a team and select different routes on their way.

Once the first member proceeds towards the target, it starts to inform other members. The other members receive the information and moves forward towards the target and accordingly the cohesion centroid moves forward. This is can be seen as if the first arrival pulls next member, and this next member does the same to one next to it,… etc.

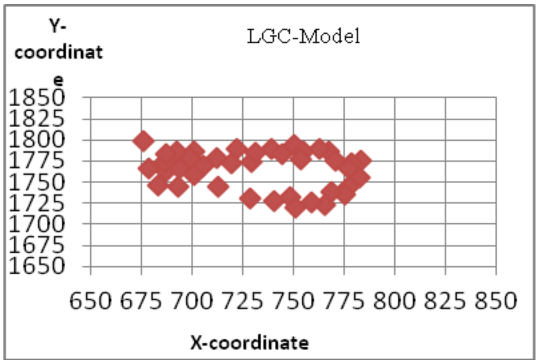

Figure 2. The Nanorobots Swarm Around the Target Location

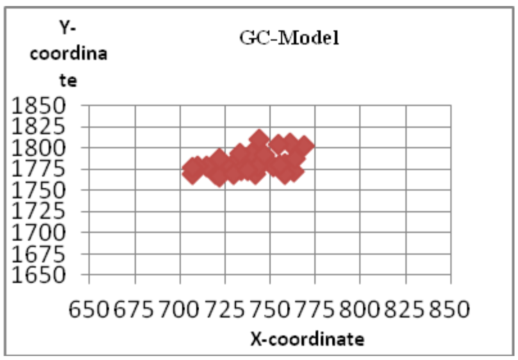

Figure 3. A Set of Individual Nanorobot Arrive at the Target Location, Congestion is Observed

Figure 2 shows all the positions of the set of nanorobots running the local-global communication model over a period of time; note that the nanorobots swarmed about the location. The region of the covered area is computed as the number of occupied cells in the grid, each cell represents (25µm × 25µm). This implies that as the number of occupied cells is 17, the nanorobots cover 10.625 µm². Comparing these results with those resulting from running the same number of nanorobots communicates via the global communication rule only, Figure 4. **Figure**Figure 3 illustrates the number of occupied cells is 9 cells covering only 5.625µm².

The results of this experiment indicate that:

1. The coverage area by the flocking nanorobots *(LGC-Model)* is about double that covered by individual set of nanorobots (*GC-Model*).
2. The swarm keeps the members bound by the cohesion force so none of the members is lost during the task.
3. Selecting different routes allows covering more area during the sweeping task.

3.2 Overcoming Local Minima Problem in Swarm Navigation by Controlling Interaction Weights

The Local Minima Problem in Swarm Navigation, presented in [24], can be described for the proposed model and according to the considered scenario as follows. Given the situation where a nanorobot detects a large number of nearby nanorobots, then each of these nanorobots modifies its velocity to move towards the cohesion centroid. If one or more of these nanorobots detects a wall and at the same time some of the other nanorobots within the avoidance zone, it may become trapped. In this trap situation, a neighbor of this nanorobot (who may not detect the same objects) will be influenced by the trapped nanorobot. In the same manner, the remaining nanorobots will be influenced by the trapped nanorobots as a result of a high cohesion weight. The other nanorobots who detect the trapped nanorobot will be influenced by the trapped nanorobot which can still significantly slow their progress. This can become worse if this set of nanorobots is assigned a task to reach or detect cells emitting a specified threshold concentration. This leads to a longer expected completion time, or even prevents the influenced nanorobots from completing the task. Considering this scenario, the swarm reaches local maxima where they cannot maintain their positions to complete the task. In this respect, a main goal of analyzing the interaction weights then is to adjust the cohesion weight in order to avoid the impacts of a high cohesion weights without losing the benefits of the supportive role of this weight in the team performance. Recall, as the cohesion rule dominates the other rules, swarm members always move as a team which prevents losing any team member during the task accomplishment.

Originally, the experiment numerically assesses the dominance of the cohesion weight in situations where the nanorobots do not detect any avoidance cases; the three flocking rules were used. The values shown in Table 1, are given for the alignment and cohesion weight as the collision avoidance weight is always 1. For this implementation, the cohesion weight is computed as the inverse of the distance to cohesion centroid (Coh_C) if the Coh_C falls within the avoidance range ($<S_d$), otherwise it set equal to one. This implies that the cohesion force is mostly inversely proportional to the distance to the centroid. The weight becomes bigger very quickly as the centroid position falls outside the avoidance range S_d whilst it *does not* become very small within the avoidance range. Hence, the cohesion weight is considered the weight controls the binding force between the swarm members. Each swarm member calculates the cohesion weight in terms of the cohesion centroids as follows:

Coh_W equals to the reciprocal of distance to cohesion weight if the cohesion centroids is less than separation distance Coh_W equals to *ONE* if the cohesion centroids is greater than the separation distance.

Table 1. The initial values of the interaction weights: $Align_w$, Coh_W and $Collis_W$ being chosen for testing the influence of the flocking rules.

Rule	Swarm Alignment		Swarm Cohesion		Collision Avoidance
Rules Weights	$Align_w$		Coh_w		$Collis_w$
IF Centroid	$Align_c$		Coh_c		$Collis_c$
	$<S_d$	$>S_d$	$<S_d$	$>S_d$	$Always$
Weights	$1/Align_c$	1	$1/Coh_c$	1	1

Figure 5 illustrates bar graph shows the weights that control the effect of the interaction forces on nanorobot movements over the first 200 frames of the simulation, according to the values shown in Figure 5. The bars sections in blue show high values of cohesion weight implies that nanorobot will be highly influenced by the nearby nanorobots, and via monitoring the trap problem can be observed. In addition, the experimentation result has shown that the cohesion weight slows the nanorobots progress, due to the high cohesion impact on swarm members.

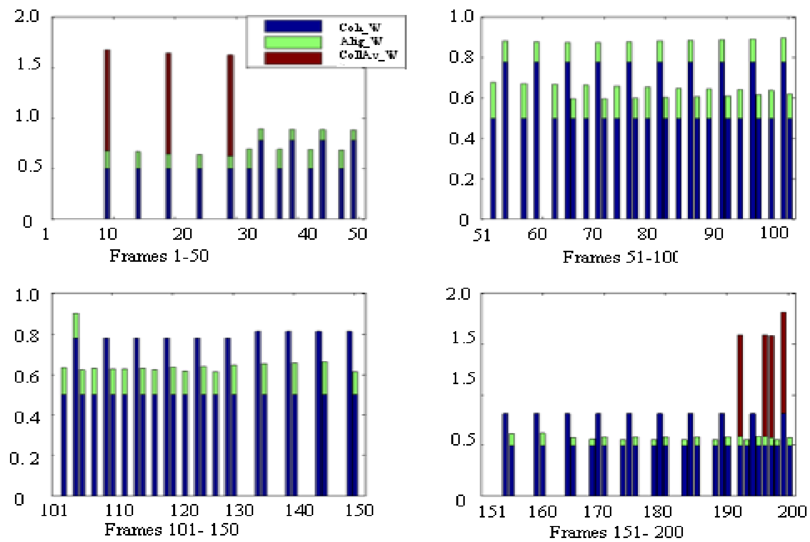

Figure 4. Initial Interaction Weights, Table 1

Slowing the progress in turn causes overcrowding in the surrounding area which is used as an indicator for examining the strength of this binding force.

In the second part of this experiment the cohesion weights are reduced; values are shown in Table 2. The cohesion weights are calculated as follows:

1. The Coh_W equals the reciprocal value for the cohesion centroid if its centroid is less than the separation distance,
2. The Coh_W equals the reciprocal of the squared centroid if its value is greater than the separation distance

Table 2. The Modified Interaction Weights: $Align_w$, Coh_W and $Collis_W$ with the Cohesion Weights Reduced

Rule	Swarm Alignment		Swarm Cohesion		Collision Avoidance
Rules Weights	$Align_w$		Coh_W		$Collis_W$
IF Centroid	$Align_c$		Coh_c		$Collis_c$
	$<S_d$	$>S_d$	$<S_d$	$>S_d$	Always
Weight	$1/Align_c$	1	$1/(Coh_c)^2$	$1/Coh_c$	1

Figure 5 illustrates the interaction weights over the first 200 frames, with the cohesion weight modified according to the values presented in Table 2. In this experiment the alignment rule dominates the other two rules. The alignment weights for the swarm members are shown in green in Figure 5. Modifying the cohesion weight has shown to be efficient in both speeding up the swarm members movements and to prevent overcrowding during movements and upon arrival.

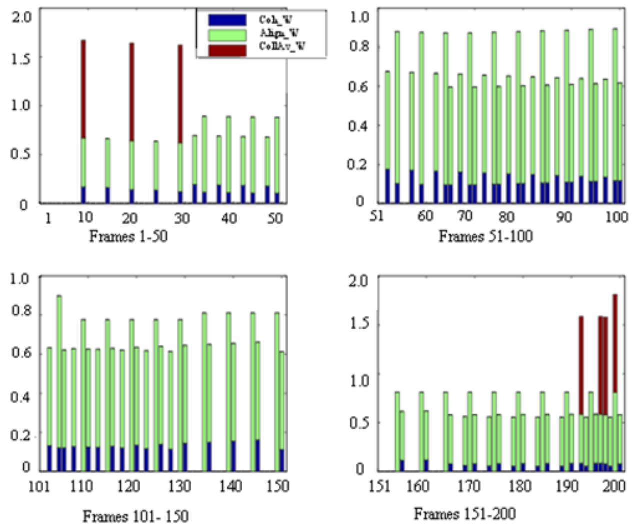

Figure 5. Modified Weights: Reduced Cohesion Weight

3.3 Grouping Swarm into Teams for Self-coordinating Swarm Members

This experiment considers using a larger group of nanorobots in the swarm. The goal for this part was to study the effect of implementing grouping technique to optimize the uniformity of arrival rate. The test aimed at investigating the optimum team size when grouping a large number of nanorobots into a set of small teams. A ratio ρ has been defined as the ratio of team size to the number of teams. The values of ρ are computed from the possible combinations of the number of teams and the team size for a specified population size.

The experiment in this section is designed as follows:

1. Specifying the number of swarm members.
2. Computing the possible combinations of team size and number of teams for a given population size. For example, in order to study the emergent behavior for a set of 36-nanorobots, the possible combinations are shown in Table 3.

Table 3. Grouping a Swarm of 36 Nanorobots: the Possible Combinations and Corresponding Ratio ρ

No. Teams β	Team Size γ	Ratio ρ
1	36	0.0278
2	18	0.11
3	12	0.25
4	9	0.44
6	6	1
9	4	2.25
12	3	4

Running the LGC −Model where the user issues the same task for the nanorobots during each run. For each trial, the completion time for the first, 50%, and 100% of arrivals is recorded. Running a large swarm is required for ensuring group performance self-coordination technique. Grouping technique has shown to be efficient in coordinating the swarm upon arrival so that they do not overcrowd around the target concentration emitters. In addition, the grouping would cover a wider area around the target position. For this purpose, a success criteria was defined; Grouping ratio ρ . Based on the observations of the swarm performance, the grouping ratio ρ is calculated depending on the swarm team size β and the number of teams δ. The following equation presents the formula used to calculate the ratio ρ:

$$\rho = \frac{\beta}{\gamma}$$

Table 4. The Effect of Varying the ρ on the Completion Time in Frames

Ratio	Completion Time in frames		
ρ	1st Arrival	50%Arrivals	100%Arrivals
0.0278	1004	1090	1400
0.1111	857	1180	1580
0.25	694	1350	1880
0.4444	570	1640	2155
1	504	1900	2340
2.25	468	2010	2410
4	464	2040	2440

Table 4 presents the completion time for reaching a designated LDL concentration, in the form of number of frames to complete the task, for the first arrival, 50%, and 100% arrivals. The results are plotted in graph shown in Figure 6, where the graph has two scales; the first scale is used to represent the number of frames to complete the task for the 50%, and 100% arrivals. The second scale is used to represent the number of frames for the first arrival with the values of the grouping ratio on the horizontal axis. From the graph shown in Figure 6, one can see that the arrival time for the 50%, and 100% arrivals, as a number of frames, decreases as the number of teams increases. This is due to the fact that a lower number of members in a team the nanorobot needs to communicate and detect leads to a fewer social interactions. As the team size reaches one, the arrival time for the all the swarm members (100% arrivals) is a minimum because the group of nanorobots become individuals moving towards the specified target with no local interactions except avoidance. This can lead to the swarm members arriving almost at the same time which results in overcrowding with respect to time at the target position. In other words, the smaller team sizes result in speeding up the arrival for the 50% of team members.

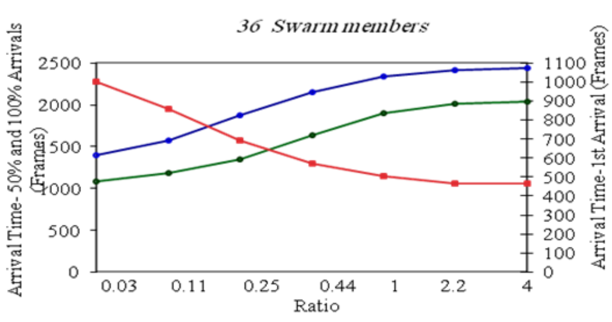

Figure 6. The Variations in First Arrival Time, Fifty Percent, and Completion Time vs Ratio

The arrival rate was plotted in Figure 7 for a swarm of 36 nanorobots and for different team sizes monitoring the arrival of the first swarm member, arrival of 50% of the swarm members, and completion time (arrival of 100% of swarm members). Figure 7 includes 6 plots representing the distribution of arrivals to the designated target location that emits the chemicals concentrations defined as threshold for the swarm members. The uniformity of arrivals, arrival rate, was plotted for: first arrival, 50% of arrivals, and 100% arrivals.

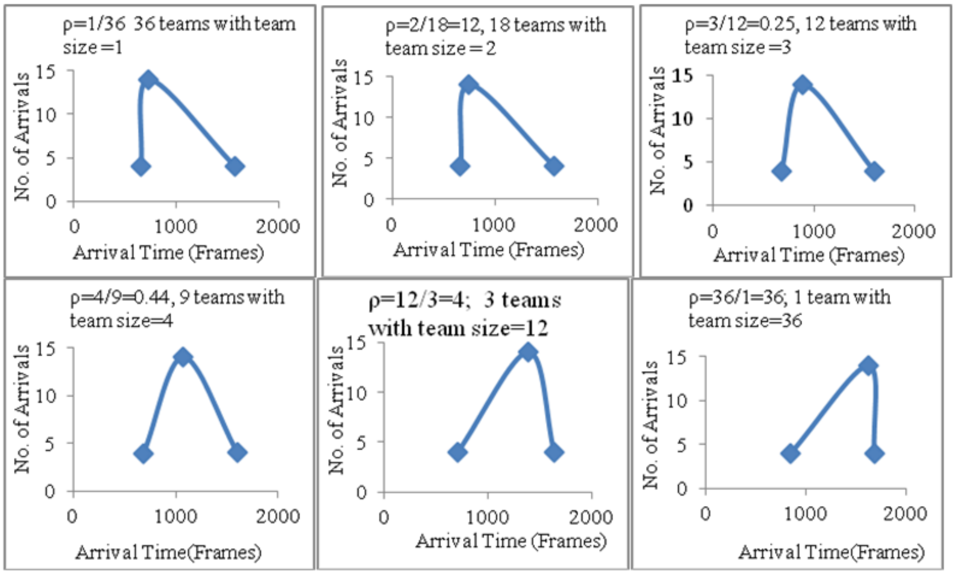

Figure 7. Grouping a Swarm of 36 Nanorobots into Teams. The Uniformity in Arrival Rate is Observed with Ratio= 0.44

The plots in Figure 7 show the curve is negatively skewed as the ratio exceeds one which implies more clustering on arrival as they arrive almost in the same time. The plots in Figure 7 illustrates a long arrival time for 50% of nanorobots, represents a big team size. A distribution for a smaller number of teams has illustrated a positively skewed distribution. This implies that the first arrival may remain for long time waiting for the rest of the team to arrive at the target position. The first arrival can play a role in passing information about *LDL* concentration detected and number of swarm members required such that the rest of team can make use of this information. The plot that satisfies a normally shaped distribution Figure 7 that is most likely zero skewed was at ρ = 0.44;i.e. ρ = 0.44 implies 9 teams with 4 nanorobots per team. Thus nanorobots in this situation can be considered to be self-coordinated as they arrive in a uniform rate.

The results presented in this section indicate that teaming technique works efficiently with reasonable combination of team size and number of teams. Main advantages of teaming technique are the reasonable arrival time for the whole team, and uniformity in the arrival rate.

4. Discussion

This section discusses the results presented in the previous section. The proposed LGC-Model allows the swarm members to interact locally and globally. This means, all the swarm members are committed to move forward with the blood stream within a team. As the first swarm member detects the *LDL* threshold concentration, it considers this is as target location and speeds up towards the target location, hence it sends electric signal to nearby swarm members. Accordingly, the team centroid, also moves forward. These local interactions lead to the progress of the team centroid which in turn leads to the movement of team members as rolling around the target location. This is seen as they are pulling each other forward and at the same time towards the target location. On arrival, swarm members within a team will cover a wider area around the target position. This prevents the nanorobots from overcrowding the target location and they are shown to appear to circle the target.

The question now is to what extent this flocking behavior is required to gain system performance. This implies considering the inputs to the flocking system and the weights that controls the influence of each rule in the flocking system. The weights corresponding to these rules control the strength of these rules and are also dependent on the sensory data. The results presented in section 3.3 have been shown that on arrival, the swarm members covers area greater using both the local and global communications. With the flocking system switched off, the covered area is less. In addition, this would enable the nanorobot to compromise between the local interaction and the global communication demands.

On the other hand, implementing the communication with the forth rule only, i.e. running the *GC –Model,* the swarm members move as individuals. In the other words, by switching the flocking rules off; i.e. suppressing all the social interactions, the nanorobots intend to

5. Conclusion

The paper presents a communication model for implementing a swarm of nanorobots performing a sweeping task to find cholesterol plaques and starts to swarm around the plaque. The proposed model assumes the nanorobot is not attacked by the white blood cells in the immune system reaction as they move inside blood arteries via flocking motion considering the speed of the blood stream to reach the target location. In addition, the proposed model assumes the nanorobots has nano control design based on onboard electrical and chemical nano scaled sensors. The nanosensors help the nanorobot detecting a specified *LDL* concentration of the target that has surface chemicals and allowing the nanorobots to receive electric signals from other swarm members and medical physician.

The proposed model integrates the decentralized movement coordination technique; uses the flocking algorithm, together with the centralized coordination of task assignment. In addition, two main enhancements were added to the common flocking algorithms, the first is filtering the inputs to the flocking system according to the requirements of each rule, and the second is use of heterogeneous weights and centroids in the flocking rules and for each nanorobot as a swarm member by grouping the swarm members into teams. The enhanced flocking algorithm is used to minimize the extreme clustering of swarm members and support the team performance. The global view is added to the system for central coordination of task assignment, cancellation and ending current task. All communications is performed via exchanging messages in the form of the electrical signals encode the LDL concentration threshold and the estimated distance to target.

The experimentation results have shown that implementing the proposed model improved the Coverage area during both the sweeping task and on arrival to target location. In addition, the implementing the proposed model helps overcoming the local maxim problem in swarm navigation. Finally, and using a large population size for the swarm a grouping technique is implemented and the experimentation results has shown to be efficient in coordinating the swarm upon arrival so that they do not overcrowd around the target concentration emitters. In addition, the grouping would cover a wider area around the target position.

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