An Ant-like Task Allocation Model for a Swarm of Heterogeneous Robots

Sifat Momen & Amanda J.C. Sharkey

Neurocomputing and Robotics Group

Department of Computer Science

University of Sheffield,

Regent Court, Portobello, Sheffield S1 4DP, UK

Email: acq07sm@sheffield.ac.uk, amanda@dcs.shef.ac.uk

Abstract. This paper addresses the issue of applying decentralised task allocation and task switching mechanisms in heterogeneous groups of robots in order to increase their ability to respond to task demand effectively. Our work is strongly inspired by the behaviour of eusocial insects (typically ants) and their behaviour of switching tasks in order to meet the changing demand. The objective of this paper is threefold: 1) identification of task allocation and task switching mechanisms in robots inspired by ants like red harvester ants, *Pogonomyrmex barbatas*, 2) developing a simple model of these mechanisms for use with a heterogeneous group of simulated robots and 3) implementing a decentralised and adaptive mechanism of updating thresholds for heterogeneous groups of simulated robots. The paper extends the use of threshold based mechanisms in homogeneous robots into the realms of heterogeneous groups of robots. Experimental results show that the incorporation of task switching mechanisms in specialised groups of robots improves the foraging efficiency and swarm energy significantly.

Keywords: collective behaviour, division of labour, foraging efficiency, heterogeneous robots, self-organisation, task switching

1. INTRODUCTION

In recent times, there has been an increasing interest in the study of swarm robotics (SR) amongst researchers in areas as different as biology and engineering. The term *swarm robotics* was first coined in 1989 by Beni and Wang in order to describe a class of cellular robots (for brief histories see [1], [27]). Erol Şahin, in 2004, defined swarm robotics as "*the study of how a large number of relatively simple physically embodied agents/robots can be designed such that a desired collective behaviour emerges through local interaction among agents and between the agents and the environment*" [2]. The concept of SR is strongly inspired by biology especially by the observation of social insects which stand as fascinating examples of how a large number of simple individuals interact with neighbouring individuals and the environment in the vicinity to create collectively intelligent systems. The concept of SR is closely related to swarm intelligence (SI) [3] in the sense that both were initially inspired by the behaviour of social insects [4]. The field has attracted considerable interest both because it offers a number of advantages for practical applications (including robustness, flexibility and scalability) and also because of its biological inspiration.

Thus far, in much of the work in the field of SR, the robots are treated as identically able to carry out simple tasks using local communication between themselves and the nearby environment (see e.g. collective box pushing [5], cooperative transport of prey items [6], construction of a nest site [7] and foraging of food items from the environment [8, 9]). However, we argue that as SR begins to be applied in situations that are more complex in terms of the number of tasks they involve, there will be a need for more specialised heterogeneous groups of robots in order to better manage the tasks. Research in social insects has shown that social insects such as ants and bees manage complicated tasks by dividing the whole task among groups of individuals, a technique sometimes referred to as *division of labour* (DOL) [25, 26].

This paper addresses the issue of division of labour (DOL) in swarm robotics by developing a model of different groups of simulated robots/agents and exploring the ways in which their ability to carry out their individual tasks results in the accomplishment of the global task. The aim of this paper is to investigate how heterogeneous groups of robots can respond to task demand effectively. We pose two main research questions in this paper: (1) will a threshold based approach (known to work well with homogeneous groups of robots) work with heterogeneous groups of robots? and (2) does a task switching mechanism in heterogeneous groups of robots improve the foraging efficiency and the net energy gained by the swarm?

The rest of this paper is organised as follows: Section 1 introduces the concept of division of labour both in the realms of social insects and swarm robotics and describes the sources of our inspiration. Section 2 gives a description of the issues to be explored in this paper and also presents a model followed by a report of experimental investigations and results in Section 3. Finally, we conclude the paper in Section 4 with a remark on our future work.

2. Division of Labour (DOL):

Eusocial insects such as ants, bees and termites are known to be capable of carrying out different tasks concurrently. This phenomenon is what is termed "*division of labour*" [10, 11, 12, 13]. Similar mechanisms are also found within the swarm robotics literature where groups of robots are able to manage tasks as required.

2.1 Division of Labour in social insects:

DOL among social insects workers is a salient feature of their organisation. It is also fundamental to their ecological success [14, 15]. Social insects are known to divide their tasks amongst groups of workers (called castes) to improve task efficiency. In addition, one of the intriguing features of their behaviour is that they are adaptive to environmental situations and able to react to changing demand by switching tasks to those for which the colony demand at that instant is high. This feature of adaptability accounts for much of their colony success [14]. Our work is highly inspired by ants such as *Pogonomyrmex barbatas* which provide a good example of task switching in social insects.

P.barbatas ants are seed eating ants [16] and are typically between 5 mm and 7 mm long. They are widely found in the south-eastern desert of Arizona, close to the New Mexican border. These ants are known to have four different castes (patrollers, foragers, nest maintenance workers and midden workers), each having a particular task. Patrollers are one of the first groups of workers to emerge in the morning. They do most of the trail laying and also assess whether it is safe to forage or not. The successful returns of the patrollers trigger the foragers to emerge out of the nest. Foragers use the direction chosen by the patrollers and ignore food sources that were not explored by the patrollers. The nest maintenance workers are involved in building and maintaining nest chambers inside the nest while the midden workers accumulate the refuse pile or midden and move it from one place to another. Further detail of their activities can be found in [16].

Red harvester ants not only carry out their own tasks but also to change to a different task if required (Figure 1). This changing ability comes into action in response to increased demand for a particular task. For instance, when there is a flood and the nest gets damaged, the need for more nest maintenance workers would become high. In such circumstances ants from inside the nest task switch and start working as nest maintenance workers [16]. However it is worth noting that not all task-switching transitions are possible. For instance, if there is a need for foragers, all the other castes can switch their tasks to foraging and assist the foragers but if there is a need for patrollers, only nest maintenance workers are found to switch their task to patrolling.

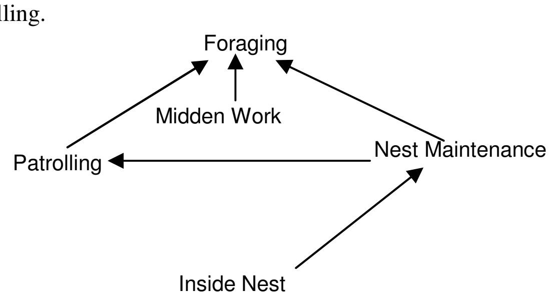

Figure 1. Task Switching in red harvester ants

2.2 Division of labour in Swarm Robotics:

In the past eight years, the field of SR has witnessed a number of developments in the areas of task allocation and division of labour. One of the earlier papers in this area was by Krieger and Billeter [8] in which a group of up to twelve mobile robots made autonomous decisions about whether to forage or rest depending on the nest energy level (which was periodically echoed to the robots in the nest from a central control station). Following this work, a number of authors have developed various ways to automatically adjust the ratio of foragers to resters. For instance, Labella, in 2004, introduced a variable delta learning algorithm [9, 17) to automatically adjust the ratio of robots undertaking the two tasks. His model was inspired by Deneubourg's learning model [18] which was developed to explain the foraging patterns observed in the *Pachycondyla apicalis* ants. Wenguo Liu and his colleagues at the Bristol Robotics Laboratory, UWE used a threshold based approach [19] to develop an adaptive threshold based mechanism for automatically adjusting the ratio of foragers to resters [20, 21] with the intention of optimising the net energy. This approach is similar to that of Labella [9,17] in the sense that the robots decide autonomously which tasks to perform via some learning mechanisms.

However, these previous studies have assumed that the robots or the simulated robots are identical (i.e. homogeneous) and are therefore able to carry out all the tasks with equal ease. We argue that this is feasible only when the complexity of the tasks is low and the number of robots involved is also low. When the complexity of the task and the number of robots involved in the problem increases, the need to divide the task among groups of robots becomes more prominent. The need for heterogeneous robot systems to tackle difficult missions has also been highlighted by various researchers in different contexts of swarm robotics (see e.g. [22, 23, 24, 9]). Numerous such examples can be found within the context of eusocial insects and one was described in section 1.1.2. With this view in mind, this paper focuses on modelling a heterogeneous group of specialised robots able to carry out their own tasks as well as switch tasks as required. In this paper, heterogeneous groups are modelled by giving a group very different threshold values compared to other groups. For instance, foragers are given a low threshold value for foraging which means that this group of robots would respond more sharply to the need of foraging compared to other task demands.

In this paper, an investigation is undertaken with the aim of exploring how task allocation and task switching behaviour in groups of heterogeneous robots affects the foraging efficiency and the net energy gained by the swarm. We conjecture that both foraging efficiency and net energy will be improved by the introduction of a task switching mechanism as this improves the flexibility of the robots' response.

3. The Model:

An agent based model (ABM) has been developed to investigate the two questions posed at the beginning of this paper (i.e. to establish whether the threshold-based approach developed in the context of homogenous groups of robots will also work with heterogeneous groups, and whether a task switching mechanism will improve their foraging efficiency.

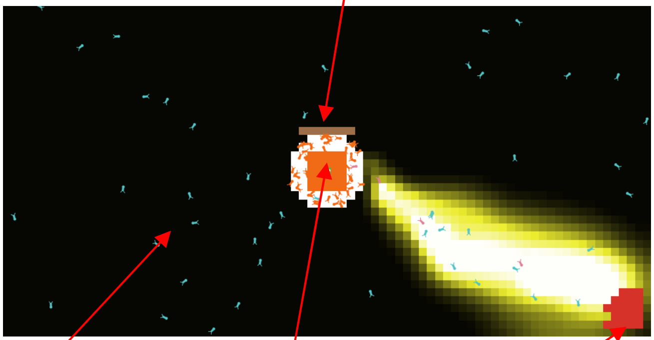

Fig 2: Snapshot of the simulation

The model places three types of agents (larvae, brood-carers and foragers) within a 40 × 20 2D environment, with the nest at the centre of the environment. The location and the tasks of the three types of castes are described as follows:

1. Larvae reside at the centre of the nest and their main task is to consume food found by foragers.

2. Brood-carers surround the larvae (and reside in the white zone) and are responsible for feeding the larvae when they are hungry.

3. Foragers, on the other hand, usually stay outside the nest and their main job is to retrieve food from the environment.

Similar spatial distributions of workers have been found in various ant species [14]. In the simulation, food appears (automatically when depleted) alternately in a clump at one of the two corners (top right and bottom right) of the environment.

3.1 Behavioural rules:

Each agent follows simple behavioural rules described as follows:

<u>A.Larvae:</u> Each larva possesses one of two states (hungry and non-hungry) and maintains a clock called *"hunger clock"* which is randomly initialised between 0 and 100 to ensure that all the larvae do not get hungry at the same time. The simulation starts with all the larvae in the non-hungry state. The rules followed by the larvae are as follows:

- After every time step, increment the *hunger clock* value by 1
- If the *hunger clock* value exceeds some threshold parameter specified for larvae, then switch to the hungry state
- If a larva is in a hungry state, it radiates signals (broadcast) to catch the attention of the brood carers
- If a hungry larva is fed, then switch to the non-hungry state and reset the *hunger clock* to 0

<u>B.Foragers:</u> Foragers can either *forage* (i.e. collect food items from the environment and bring them back to the dump area of the nest) or *rest* inside the nest. However, they have a higher propensity for foraging than resting. This is implemented by means of a threshold based approach initialised with low t_f (threshold for foraging) and high t_r (threshold for resting). At every simulation step, foragers update their threshold values as described in Table I.

Each forager also maintains two types of clocks: a *searching clock* (indicating the amount of time spent searching outside the nest) and a *resting clock* (indicating the length of time resting). Foragers follow the following behavioural rules:

- Increment the *searching clock* while searching for food
- Increment the *resting clock* if resting inside the nest
- When food is detected, take one food item and carry it back to the dump area of the nest and while going back drop pheromones on patches
- When the dump area is detected unload the food item there, rotate 180^0, set *searching clock* to zero and start a random search for the food
- If pheromone is detected when looking for food, follow the pheromone concentration to the food source
- Update the threshold values at each step of the simulation according to Table I and use the threshold values to decide whether to forage or rest.

<u>C .Brood-carers:</u> Brood carers can either rest or brood care (i.e. feed the larvae). They usually rest within the white zone of the nest (figure 2) and simply react to the needs of larvae by feeding them when required. This is implemented by initialising them to have high t_{bc} (threshold for brood caring) and low t_r (threshold for resting) and allowing them to update the threshold values depending on the stimulus received. Each brood carer follows the following behavioural rules:

- if it senses the *hunger-signal* of the larvae, it increases its chance of feeding the larvae by reducing its t_{bc} and increasing t_r.

When it decides to feed the larvae, it goes to the dump area, collects the food, approaches the larvae and feeds one of the hungry larvae

	Threshold for foraging (t_f)	Threshold for resting (t_r)	Reason
Successful in carrying food item back to the nest	Reduce	Increase	If the forager is successful in carrying food items back to the nest, it might mean that there are more food items in the environment to forage. The successful return of the food items thus triggers an increased chance of foraging and reduced chance of resting.
Searching clock > max-searching-clock-allowed	Increase	Reduce	If the forager spends too long searching for food, it might mean that there are not sufficient food items in the environment to forage. The foragers should therefore increase their likelihood of resting and reduce their chance of foraging.
Resting clock > max-resting-clock-allowed	Decrease	Increase	If the forager spends too long resting inside the nest, it might mean that they were resting too long inside the nest and their might already be some food available outside

Table I: Adaptation rules for foragers

4. Experiment

In order to test the two questions posed in this paper, the experiment was carried out in two phases. In the first phase the agents follow the behavioural rules outlined in section 2. In the second phase, a task switching mechanism is introduced. Brood carers, in this phase, also take part in the foraging activity if the food in the dump area falls below some threshold value. For the second phase, brood carers follow an extra behavioural rule stated as follows:

When in the dump area, check how much food is left. If the food available in the dump area is below some threshold value, then reduce the threshold for foraging (equation 1)

$$t_f = t_f - \Delta \qquad (1)$$

where Δ indicates the motivation level for brood carers to switch tasks to foraging.

As the agents move around in the environment, they can gain or lose energy. They gain energy when they are successful in carrying out their respective tasks (such as successful retrieval of food for foragers, successful feeding of larvae for brood carers and successful consumption of food for brood/larvae) and lose energy when doing some work. Table II indicates the energy gained or lost by different types of agents ('+' indicates the gain of energy while '-'indicates the loss of energy):

Activities	Energy gained/lost	Agent that loses or gains energy	Remarks
Foragers looking for food	-2 per 10 unit steps	Foragers	Energy is consumed while searching for food
Foragers resting	-1 per unit 10 steps	Foragers	Less energy is lost
Foragers carrying food	-4 per unit 10 steps	Foragers	More energy is consumed to carry the food
Successful retrieval of food by foragers	+200	Foragers	Energy gained due to the successful retrieval of food
Brood carer carrying the food from the dump area to feed the larvae	-4 per unit 10 steps	Brood carer	Energy lost in carrying the food from dump area to the centre of the nest
Successful in feeding the larvae	+3	Brood carer	Brood carers gain energy in being able to feed the larvae properly

Hungry brood	-4 per unit 10 steps	Brood	When the brood is hungry they tend to lose energy
Brood fed	+3	Brood	When a hungry brood consumes food, it gains energy

Table II: Energy expended/gained for various activities

The net energy gained by the swarm is then calculated using equation 2.

$$Net \quad Energy = \sum_{i=1}^{n_f} E_{f_i,1500} + \sum_{j=1}^{n_{bc}} E_{bc_j,1500} + \sum_{k=1}^{n_b} E_{b_k,1500} \qquad (2)$$

where n_f, n_{bc} and n_b are the number of foragers, brood carers and brood respectively and $E_{f_i,1500}$, $E_{bc_j,1500}$ and $E_{b_k,1500}$ are the individual energy of the forager, brood carer and brood respectively at 1500th simulation time steps.

4.1 First phase of the experiment:

Experiment trials	Total amount of food Collected	Net energy gained	Foragers' energy	Brood energy	Brood carers' energy
1	77	2016.4	1912	34.2	70.2
2	73	1118	1016	31.8	70.2
3	71	1108.1	954.9	62.2	91
4	80	2521.7	2397.3	43.8	80.6
5	117	9195.5	9085.5	37.2	72.8
6	79	2573.4	2381.8	82.4	109.2
7	127	10777.1	10625.1	61	91
8	118	9557.6	9336.8	98.6	122.2
9	94	4990.5	4882.5	35.2	72.8
10	142	13975.4	13779	84.6	111.8
11	83	2938.5	2817.3	43.2	78
12	72	1159	1063.8	30.2	65
13	106	6825.8	6678.2	56.6	91
14	72	740.2	651.4	26.4	62.4
Average	93.65	4964.09	4827.26	51.96	84.87

Table III: Results for Phase 1 of the Experiment

The experiment was carried out 14 times each lasting for 1500 simulation steps. The results of experiment are depicted in table III.

4.2 Second Phase of the experiment:

The second phase of the experiment was also carried out 14 times each lasting for 1500 simulation steps for various values of Δ (the motivation level of brood carers to switch their tasks to foraging). The overall result is depicted in table IV and the corresponding graphical displays in Fig 3 and Fig 4.

Δ	Average amount of food Collected	Average amount of food collected by brood carers	Average amount of food collected by foragers
0 (from first phase)	93.65	0	93.65
0.1	93	1.9	91.1
0.3	96.9	4.8	92.1
0.5	110.9	7.4	103.5
0.7	99.9	7.6	92.3
0.9	112	9.9	102.1

Table IV: Results for Phase 2 of the Experiment

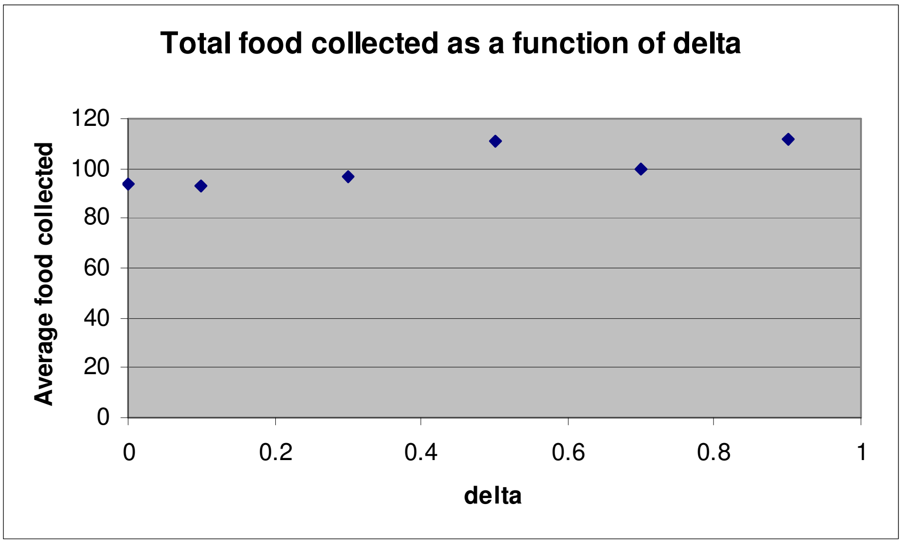

Figure 3: Total amount of food collected as a function of delta

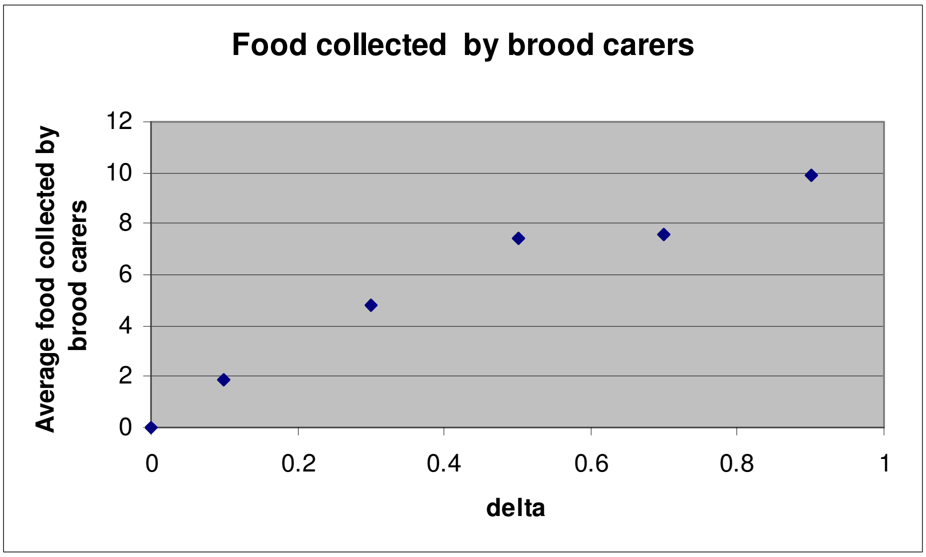

Figure 4: Food collected by brood carers as a function of delta

Figure 4 shows that the average amount of food collected by brood carers has a linear relationship with Δ (product moment correlation coefficient = 0.97). Regression analysis reveals the relationship between the food collected by brood carers (f_{bc}) and Δ as

$$f_{bc} = 0.89 + 10.51\Delta \tag{3}$$

Figure 5 shows that the incorporation of task switching improves the swarm energy by more than double than in the case of no task switching. Furthermore, results in Table IV indicate that the incorporation of task switching improves the overall foraging efficiency (the total amount of food collected).

Such mechanisms would be highly beneficial in the context of heterogeneous robot systems where specialised robots are grouped to carry out group-specific tasks. Both their efficiencies and swarm energy can be improved by employing task switching behaviours between the groups.

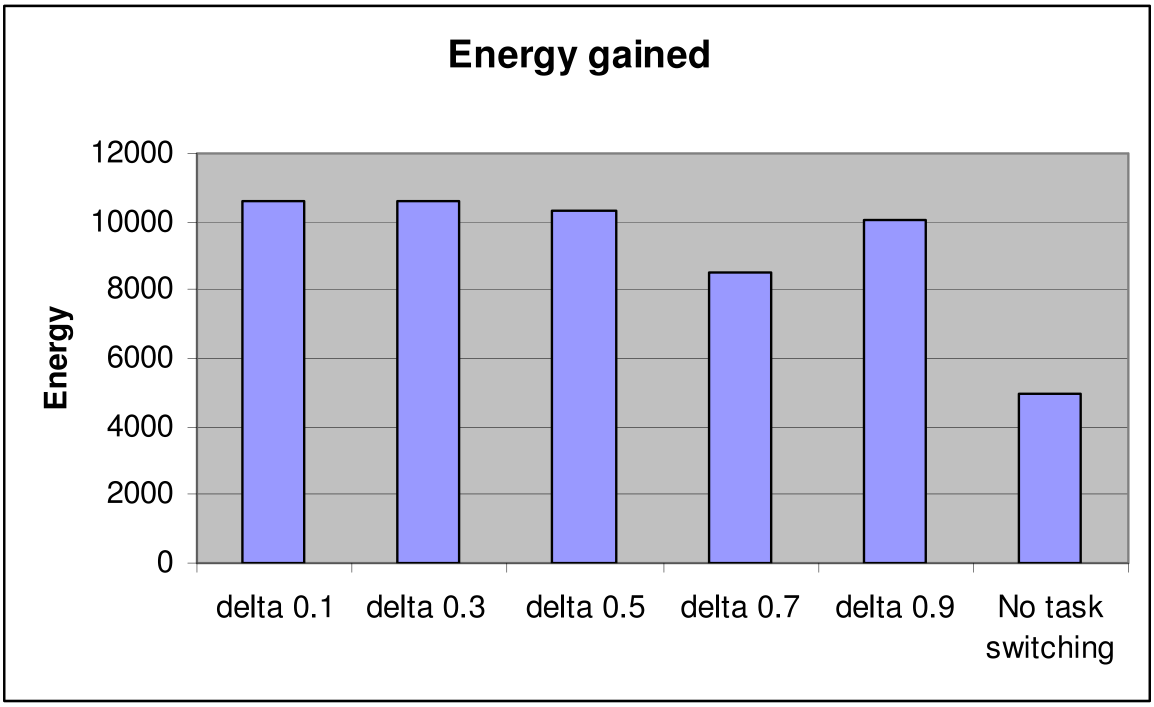

Figure 5: Net energy gained by the swarm

5. Conclusion:

We have presented a task allocation and task switching model for heterogeneous groups of autonomous mobile robots/agents that adhere to the swarm robotics' principles of local control and local communication. We have shown that the foraging efficiency and the net energy gained by the swarm are affected by the degree of task switching. A threshold based approach has been embraced for the task switching mechanisms and an adaptive mechanism introduced for updating the thresholds of the simulated robots. The model was inspired by the behaviour of social insects, in particular that of the red harvester ants *Pogonomyrmex barbatas*. Simulation results demonstrate that agents are able to perform tasks adaptively, flexibly and efficiently which suggests that the threshold based mechanism works well in the heterogeneous environment as well. It further shows that introduction of the task switching mechanism improves both the foraging efficiency and the net energy gained by the swarm significantly. Such a result would be highly beneficial in the case of heterogeneous groups of robots carrying out more than one task concurrently.

Our future work will concentrate on investigating how the distribution of food in the environment affects the foraging efficiency and the net energy gained by the swarm. We also plan to develop and empirically evaluate the effectiveness of different task switching algorithms in the context of heterogeneous robot systems.

REFERENCES

[1] Beni, G., "From Swarm Intelligence to Swarm Robotics", In Swarm Robotics, (Eds) Erol Şahin and William M. Spears, LNCS 3342, pp: 1 – 9, (2004)

[2] Şahin, E., "From sources of inspiration to domains of application", In Swarm Robotics, (Eds) Erol Şahin and William M. Spears, LNCS 3342, pp: 10 – 20, (2004)

[3] Beni, G., Wang, J., "Swarm Intelligence in Cellular Robotic Systems", Proceeding of NATO Advanced, Workshop on Robots and Biological System, (1989)

[4] Sharkey, A.J.C., "Robots, Insects and Swarm Intelligence", Artificial Intelligence Review, vol: 26, pp: 255 – 268, (2006)

[5] Kube, C.R., Zhang, H., "The use of perceptual cues in multi-robot box pushing", IEEE International Conference on Robotics and Automation, pp: 2085 – 2090, (1996)

[6] Kube, C.R., Bonabeau, E., "Cooperative transport by ants and robots", Robotics and Autonomous Systems, vol: 30, pp: 85 – 101, (2000)

[7] Parker, C.A.C., Zhang, H., Kube, C.R., "Blind Bulldozing: multiple robot nest construction", Proceedings of the 2003 IEEE/RSJ Conference on Intelligent Robots and Systems, pp: 2010 – 2015, (2003)

[8] Krieger, M.J.B., Billeter, J.B., "The call of duty: Self organised task allocation in a population of up to twelve mobile robots", Robotics and Autonomous Systems, vol: 30, pp: 65 – 84, (2000)

[9] Labella, T.H., Dorigo, M., Deneubourg, J.L., "Efficiency and task allocation in prey retrieval", ed. A.J. Ijspeert et.al, BioADIT 2004, LNCS 3141, pp: 274 – 289, (2004)

[10] Oster, G.F., Wilson, E.O., "Castes and ecology in social insects", Princeton University Press, Princeton, (1978)

[11] Robinson, G.E., "Regulation of division of labour in insect societies", Annual Review Entomology, vol: 37, pp: 637 – 665, (1992)

[12] Bonabeau, E., Dorigo, M., Theraulaz, G., "Swarm Intelligence: From natural to artificial systems", Oxford University Press, (1999)

[13] Hölldobler, B., Wilson, E.O., "The Ants", The Belknap Press of Harvard University Press Cambridge, Massachusetts London, England, (1990)

[14] Bourke, A.F.G., Franks, N.R., "Social evolution in ants", Princeton University Press, (1995)

[15] Franks, N.R., "Ants", Encyclopaedia of Insects, ed. V.H. Resh and R.T. Carde, Academic Press, pp: 29 – 32, (2003)

[16] Gordon, D.M., "Ants at work: how an insect society is organized", The Free Press, (1999)

[17] Labella, T.H., "Division of labour in groups of robots", PhD thesis, Universite Libre de Bruxelles, (2007)

[18] Deneubourg, J.L., Goss, S., Pasteels, J.M., Fresneau, D., Lachaud, J.P., "Self-organization in ant societies (III): Learning in foraging and division of labour", From individual to collective behaviour in social insects, (Eds) J.M. Pasteels and J.L. Deneubourg, Experientia Supplementum, vol: 54, pp: 177 – 196, (1987)

[19] Bonabeau, E., Theraulaz, G., Deneubourg, J.L., "Quantitative study of fixed threshold model for the regulation of division of labour in insect societies", Proceeding of the Royal Society of London B, vol: 263, pp: 1565 – 1569, (1996)

[20] Liu, W., Winfield, A.F.T., Sa, J., Chen, J., Dou, L., "Towards energy optimisation: Emergent task allocation in a swarm of foraging robots", Adaptive Behaviour, vol: 15, no: 3, pp: 289 – 305, (2007)

[21] Liu, W., Winfield, A.F.T., Sa, J., Chen, J., Dou, L., "Strategies for energy optimisation in a swarm of foraging robots", ed. E. Şahin, W.M. Spears and A.F.T. Winfield, Swarm Robotics 2006, LNCS 4433, pp: 14 – 26, (2006)

[22] Momen, S., Amavasai, B.P., Siddique, N.H., "Mixed species flocking for heterogeneous robotic swarms", IEEE Eurocon 2007, The international conference on 'computer as a tool', pp: 2329 – 2336, (2007)

[23] Momen, S., Sharkey, A.J.C., "An ant-like task allocation model for heterogeneous groups of robots", 4th European Meeting of IUSSI 2008, pp: 117, (2008)

[24] McLurkin, J.D., "Analysis and implementation of distributed algorithms for multi-robot systems", PhD thesis, MIT, (2008)

[25] Jeanson, R., Fewell, J.F., Gorelick, R., Bertam, S.M., "Emergence of increased division of labour as a function of group size", Behav Ecol Sociobiol, vol: 62, pp: 289 – 298, (2007)

[26] Anderson, C., McShea, D.W., "Individual *versus* social complexity, with particular reference to ant colonies", Biol. Rev., vol: 76, pp: 211 – 237, (2001)

[27] Sharkey, A.J.C., "Swarm robotics and minimalism", Connection Science, vol: 19, no: 3, pp: 245 – 260 (2007)