# Pattern Formation in Homogeneous and Heterogeneous Swarms: Differences Between Versatile and Specialized Agents

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***Abstract*— In collective robotics, researchers are successfully using models derived from swarm insect behavior to solve problems like coordination or task allocation. It is often assumed that in a homogeneous group of agents, every agent has to become more complicated when the complexity of the task increases, which decreases simplicity of design and robustness. Role diversification and therefore task specialization within a group may help counter the need for more complex agents. Because experiments on self-organization and dynamic task allocation in robot populations focused mainly on homogeneous groups, the relation between these models and pre-specified role diversification remains mainly unknown. In this work the interchangeability of homogeneous and heterogeneous agent populations is investigated. It is shown that in a simple simulated environment, a mixed population of specialized agents can not be easily substituted by a homogeneous group of multi-tasking agents. Results lead to the conclusion that the ability of dynamic task switching, i.e. adaptive task allocation in respect to changes in the environment, have strong effects on the behavior on a population level. Although a pre-defined heterogeneous group can produce the same result for a given environment and a specific population composition, the group behavior differs when the environment changes.**

## I. Introduction

Collective Robotics is a growing research area, which tries to solve problems by using groups of robots instead of single robots. By making this step, aspects like coordination and communication become a major concern.

The social organization of various animal species appears to emerge dynamically, i.e. without centralized control [1], [2]. In models that try to explain these observations, role diversification is assumed to originate mainly from local interactions, rather than from morphological differences. Robot experiments, inspired by these models, therefore have been carried out almost exclusively with robots of identical shape and function (e.g. [3]). Although dynamic task allocation emerged in these experiments and was efficient in terms of robustness, flexibility and simplicity of design, up till now they did not result in systems that perform very complicated tasks. The obvious solution would be to use more complicated (pre-specified, multi-tasking) robots, but this goes at the expense of the advantages mentioned above. Furthermore, there is an upper limit to such complicatedness due to domain related design limitations. For example, in the case of nano-robotics there are obvious size restrictions, thus necessitating pre-specified diversification among agents [4]. Especially this field, where the emphasis is on the use of large heterogeneous groups of small robots, would benefit from the exploitation of inherent dynamic properties. Therefore, what is needed is a trade-off between pre-specification and dynamic task allocation. Inspiration for this can be found by looking at biological systems, in which role diversification incorporates both morphological/functional differences and self-organized pattern formation [5], [6]. However, the exact relationship between these two phenomena is unclear. In the recent past other experiments on heterogeneous robot populations have been carried out [7] investigating the collaboration of robots with different sensing capabilities through evolution, but more work is needed to understand the underlying principles which then could be exploited.

In this work, the interchangeability of a heterogeneous robot population with a homogeneous population for a divisible task (i.e. the task can be divided into more or less independent sub tasks) is investigated. Does the behavior of a robot population change, if a homogeneous population of multi-tasking robots is replaced by a heterogeneous population consisting of specialized agents for different sub tasks? To answer this question different populations of agents were simulated in an abstract environment and the patterns produced over time analyzed. Because the highest discrepancy between the populations was found in an enclosed environment, main focus of the analysis is on agent behavior near walls. The experimental setup and the agent types used are described in section II followed by a brief overview of previous results obtained from group composition in heterogeneous populations. The results of the homogeneous populations compared to heterogeneous ones are shown in section IV and reasons for the differences found are explained.

## II. Experimental Setup

In the experiments described here, the environment described in [8] was used, a 2-dimensional simulated world which contains objects that are either ”particles” or agents. The particles fill up 65% of the area and the remaining space is populated by a group of 100 agents. All agents initially start in the middle of the world with random headings and spread out after the experiment starts. The environment is discrete, i.e. formed as a grid containing x quadrants. An agent is always located in the center of a quadrant and can turn over angles of 45 degrees, whereas a particle is of the size of a quadrant and hence covers it completely. All simulations were performed in a toroidal world as well as in a closed area and were run for 300,000 time steps. At each time step, all agents where consecutively activated. For each parameter setting described in sections III and IV 10 runs were performed.

The collection of agents was either homogeneous or heterogeneous. In the heterogeneous case, the world is inhabited by 50 Bull-dozer-type agents (”Dozers”) and 50 grabber-type agents (”Grabbers”). In case of a homogeneous group, only one agent type (the GrabDozer) was used that combines the behavior of both Grabbers and Dozers. Depending on the structure of the local environment, a GrabDozer switches between Grabber and Dozer activity. A detailed description of each type of agent is presented below.

The agents drop a constant amount of artificial ”pheromone” every timestep. A very simple diffusion and evaporation model is used, i.e. the pheromone is represented by a float variable at every quadrant and diffusion (not influenced by particles) and evaporation are calculated every time step.

### A. Dozers

Dozers move straight forward and push any single particle that is directly in front of them, until it is positioned against the wall or a pile of other particles (a pile is defined as a conglomeration of at least two particles). If Dozers collide with an obstacle (wall, another agent or a pile) they change their direction randomly (left or right) by turning over an angle of 45 degrees. A Dozer may lose its particle with a probability proportional to the distance pushed, after which the agent turns 45 degrees in a random direction. Dozers also continuously deposit an artificial pheromone. This pheromone triggers the behavior of Grabbers.

### B. Grabbers

Grabbers can grab and carry particles (also when turning) instead of just pushing them ahead. In case they do not hold a particle, Grabbers move straight forward, until they encounter an obstacle. If this obstacle is a wall or another agent, they turn 45 degrees in a random direction. If they run into a particle, and depending on the level of pheromone at that location, they grab it. The probability of grabbing increases with the local pheromone concentration. In case a Grabber already holds a particle, it moves straight ahead until it encounters an obstacle (wall, agent or box) after which its turns 45 degrees in a random direction. The probability of dropping the particle

Fig. 1. Example of resulting structure after 300000 time steps for a population of Dozers. Each white pixel represents a particle and each black pixel represents an empty spot. The grey borders correspond to surrounding walls.

increases with decreasing pheromone level and the distance the particle was carried. Grabbers continuously drop pheromones with same intensity as Dozers.

### C. GrabDozers

The aim of our work is to establish the possible effects of division of labor by task specialization. To this end, we investigated different Dozer:Grabber ratios in previous experiments [8]. In this paper we extend these experiments by comparing the patterns produced by a mixed collection of the two types of agents with specialized activities (dozing and grabbing) with those brought about by a single, versatile type of agent the GrabDozer - that is able to perform the activities of both Dozers and Grabbers.

When encountering a particle, a GrabDozer can switch between ”pushing” and ”carrying” behavior, depending on the pheromone level at its location. The decision making process follows the same rules as used in a Grabber when encountering a particle. If the pheromone level at that location exceeds a threshold, the GrabDozer grabs the particle; if not, it behaves as a Dozer and pushes it one step forward. If no particle is ahead, a GrabDozer will move straight on.

### D. Measurements

The patterns that emerge as a result of the activities of the agents are nest-like structures that, to a varying degree, consist of ”corridors” and ”chambers” (see Fig.1).

The structure of the pattern was captured by calculating a ”structural complexity” value which gives a rough estimation on number and size of chambers and corridors in the structure. Structural complexity is measured as the information dimension [9]. Starting point is a grid, covering the pattern, with variable quadrant size. Entropy is calculated on the basis of three classes: a grid quadrant either consists completely of white pixels, black pixels or contains both. Therefore, the entropy for a given grid size x is:

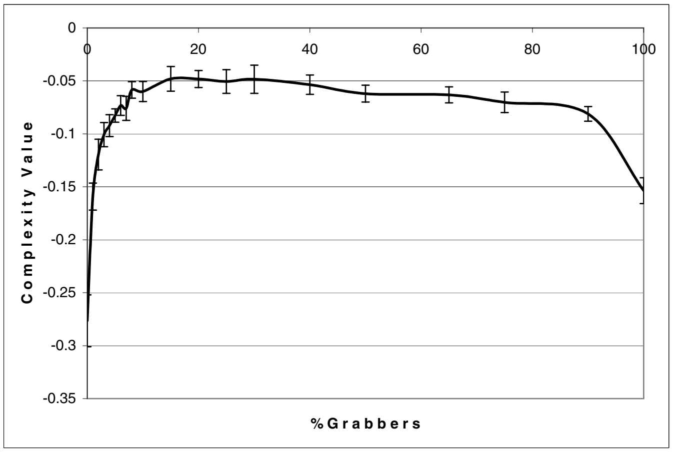


Fig. 2. Complexity measurement for populations of varying compositions (abscissa = percentage of grabbers) in an enclosed world. Error bars are 95% confidence intervals.

$$E(x) = -\sum_{i=1}^{3} p_{x,j} \cdot log_3(p_{x,j}) \tag{1}$$

where $p_{x,j}$ is the probability that a quadrant with side length $x$ belongs to class $j$. The structural complexity is then given by the slope of the regression of $E(x)$ for growing values of $x$ starting with two. If the complexity value for a given pattern is high, the structure is less complex, e.g. many wide corridors and large compact conglomerations of particles. Free standing particles decrease the value, i.e. can be seen as "noise".

## III. Results from Previous Experiments

In earlier experiments [8] it was shown that Dozers keep areas particle-free by pushing particles towards the nearest wall or pile. In contrast, Grabbers carry particles away and tend to drop them in free areas with a lower pheromone concentration (i.e. a lower density of agents). By removing particles from walls (that cannot be pushed anymore by Dozers) Grabbers prevent the system from freezing into an attractor state. But although heterogeneous populations continuously change their environment, the complexity of the built structure always appears to converge to a particular value that depends on Dozer:Grabber ratio and environmental constraints such as enclosing wall and average pheromone concentration (Fig.2).

Surprisingly, for a considerable range in the Dozer:Grabber ratio, the produced pattern is quite robust. Outside of this "stable range", the resulting pattern can change very fast with changing ratio and is also sensitive to the presence of borders (as in a closed world) and pheromone level.

In our previous work, we studied the effects of three experimental conditions (only one type of agents deposits pheromones, all agents drop pheromones in a toroidal world, and all agents drop pheromones in enclosed world) on pattern formation by a mixed group. The findings can be summarized as follows:

- If grabbers do not drop pheromones, the patterns produced by the mixed population with increasing percentage of grabbers converge towards the patterns produced by a Dozer-only group. This is due to the decrease in the overall pheromone concentration (caused by dwindling number of Dozers) and therefore decreasing activity of grabbers.
- In a toroidal world with Grabbers dropping pheromones, the results converge to the structure built by a homogeneous Grabber-population. With increasing percentages of Grabbers, the number of particles that are removed from walls exceeds the number of particles that are being pushed to walls. This results in an increasing number of free particles in the environment.
- In a enclosed world with all agents dropping pheromones, the probability of a structure containing just one central pile increased with an increasing percentage of Grabbers. A constellation of 10 Dozers and 90 Grabbers always produced this one-pile structure. If the number of grabbers is further increased, the particular pattern can only be found in half of the runs for an all Grabber population.

We presumed at the time that the reason for this behavior is the higher concentration of pheromone at walls. Agents are likely to follow walls due to 45 degree avoidance movements when bumping into a wall, therefore spending more time near walls, which results in a higher concentration of pheromones and finally a higher activity of grabbers in this area. Hence, the amount of particles carried in the area along the border is above average, facilitating the process of moving particles away from the wall.

We were able to prove this presumption in later experiments by measuring the average amount of pheromone in the fringe of the enclosed world compared to the overall concentration. Figure 6 shows that for a population of a Dozer:Grabber ratio of 50:50, the average pheromone concentration in the fringe is not significantly different from the overall concentration, whereas the concentration in the 10:90 case is about 2.5 times higher. This is also reflected in the increased grabbing behavior within the fringe region (Fig.8).

## IV. Results

The crucial difference between the current simulation and those of the previous experiments is that now the agents adapt their behavior and hence the composition of their population in terms of dozer and grabber activities in accordance to local changes in the structure of the environment. In the earlier experiments no such "dynamic task allocation" was possible because the number of dozers and grabbers was fixed for a particular run.

To investigate how patterns in the distribution of particles change if the agents conditionally switch between grabber- and dozer activities, a new agent type, the GrabDozer was introduced (see II-C for details). Because the action of a GrabDozer depends on local pheromone concentrations when encountering a particle, the ratio of grabbing agents to pushing agents varies in accordance to current environmental conditions. To

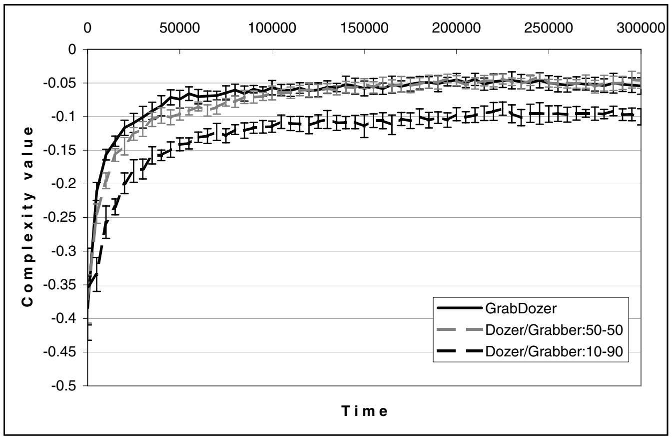


Fig. 3. Complexity measurement over time for a GrabDozer group in a toroidal world. Error bars are 95% confidence intervals.

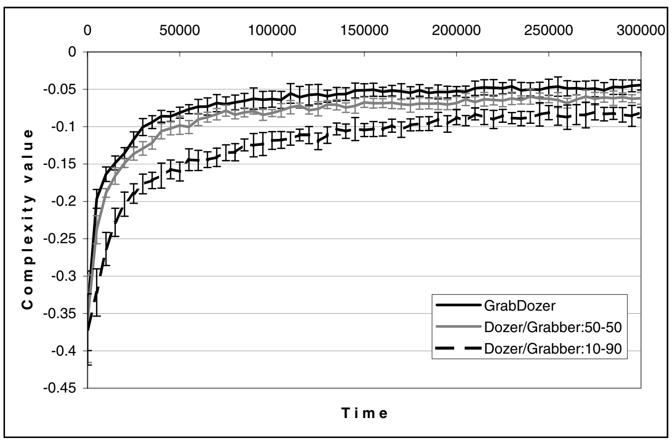


Fig. 4. Complexity measurement over time for a GrabDozer group in an enclosed world. Error bars are 95% confidence intervals.

compare the effects of a homogeneous population of flexible, versatile agents (GrabDozers) with those of a heterogeneous population consisting of fixed numbers of inflexible specialists (Grabbers and Dozers), experiments were run in both an enclosed and a toroidal environment. The same measurements were used as in the previous experiments

As can be seen in Fig.3 the homogeneous population of GrabDozers produces patterns in a toroidal world that have comparable complexity values to those brought about by a heterogeneous population consisting of 50% Grabbers. A visual examination of the produced patterns shows that both types of agents produce comparable structures (i.e. the number, size and distribution of chambers and corridors are approximately the same). The population with a Dozer/Grabber ratio of 10:90 produces visually the same structures, which is not directly reflected in the complexity values. This is due to a higher amount of free standing particles in the environment compared to the other populations, therefore leading to lower values. Also the behavior over time of GrabDozers matches those of a mixed population of Grabbers and Dozers relating to the measured complexity.

Fig. 5. Sample result after 300000 time steps for a GrabDozer group. Grey lines depict walls, white areas particles and black areas free space.

The complexity value of the patterns created by GrabDozers in an enclosed environment is comparable to that in a toroidal world (Fig.4). The values for mixed populations of Grabbers and Dozers in an enclosed environment, however, are significantly lower. Looking at sample pictures reveals that GrabDozers build a single large conglomeration in the center and a corridor along the wall (Fig.5). The same result was obtained by a heterogeneous population with 90% Grabbers in the earlier experiments. Because GrabDozers in a toroidal world, like a 50:50 Grabber/Dozer population, do not assemble such central structures, it is of interest to study the effect of borders in more detail.

Our previous findings indicated that higher pheromone concentrations near walls (due to emergent wall following) compared to open areas might be responsible for the creation of a central clump of particles. To further investigate this, the average amount of pheromones in the fringe region (up to 5 quadrants from wall) compared to the overall concentration in the environment was measured for all three groups (see Fig.6). It can be clearly seen that in the case of GrabDozers the amount of pheromones in the fringe almost immediately builds up and levels off at 2.5 times the overall average. This coincides with the emergence of a central pile which also stabilizes around the same time. In experiments with mixed populations in an enclosed world, the average pheromone concentration in the fringe at first does not differ from the global average. After about 100000 time steps it raises slowly in the 90% Grabber populations but stays almost constant at a low value in the 50% Grabber runs.

The percentage of quadrants covered by particles in the fringe area, strongly correlates to these pheromone measurements (Fig.7). With raising pheromone level, more particles are moved out of the fringe and into the center of the environment. This increase of free space along the wall in combination with the wall-following behavior of the agents and the consequential increase in pheromone concentration creates a positive reinforcement loop. The higher the average pheromone concentration, the more particles are grabbed and moved, which

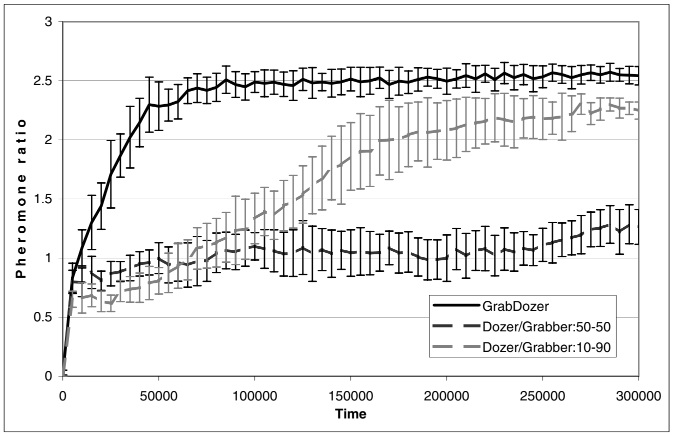


Fig. 6. Ratio of pheromone concentration in the fringe (5 quadrants wide) of the environment. Y-Axis: average pheromone concentration in fringe divided by average pheromone concentration in environment. Error bars are 95% confidence intervals.

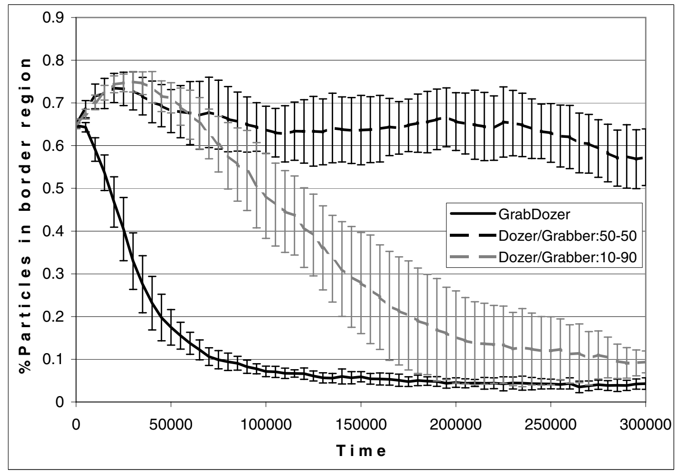


Fig. 7. Percentage of particles in the fringe (5 quadrants wide) of the environment. X-axis shows time steps of experiment. Y-Axis shows $\#particles/\#quadrants$. Error bars are 95% confidence intervals.

creates more space along the walls, thus allowing more agents to travel there. This in turn implies that they collide more often with particles along the wall, which consequently will be removed faster. In mixed populations Dozers push particles to the wall but do not react to pheromones. They thus counteract the reinforcement outlined above by moving particles back into newly created free spaces around the boundaries. In the 50% Grabber population, this outwards movement of particles is so strong that no reinforcing process starts. In the 90% group it slows down the process considerably, but in the end the majority of Grabbers is responsible for a sufficient relocation of particles away from the borders.

The pushing behavior of GrabDozers is different to that of Dozers. A GrabDozer that currently pushes a particle towards a wall, is likely to grab it and carry it away when the local concentration of pheromone position is high enough. This means that a GrabDozer is likely to change its behavior the closer it gets to a wall, therefore further increasing grabbing activity at the boundary.

In preliminary experiments with GrabDozers it was found that the average number of particles grabbed in the fringe region was equal or less than performed by heterogeneous populations with more than 40% Grabbers. This contradicts the explanation given above, since the latter would suggest a higher grabbing activity on average along the borders because of higher pheromone concentrations.

To investigate this discrepancy, the grabbing activity (number of agents currently grabbing a particle in the fringe) over time was recorded (Fig.8). Because the composition is fixed for the heterogeneous populations, the grabbing activity levels off to a value depending on number of Grabbers and the average pheromone concentration. For the GrabDozers, the grabbing activity at first is significantly higher than for a 50% mixed population, but drops soon after to a significantly lower level.

These state of affairs can be explained as follows., In a GrabDozer population most agents which encounter a particle at or near the rim of the (initially small) conglomeration, will push it because the pheromone concentration tends to be low at that location. The high rate of pushing behavior and therefore low rate of grabbing around the rim , keeps the conglomeration together. As a consequence, particles are transported from the border of the world to the growing pile in the centre; the number of free particles decrease at the boundaries of the environment and this results in a decreased grabbing activity simply because over time there are less particles to grab. In other words, an initial rise in the grabbing activity of GrabDozers is sufficient to quickly remove particles from the wall and to assemble a central pile; as soon as this pattern is stabilized it will no longer be destroyed, because grabber activity has declined.

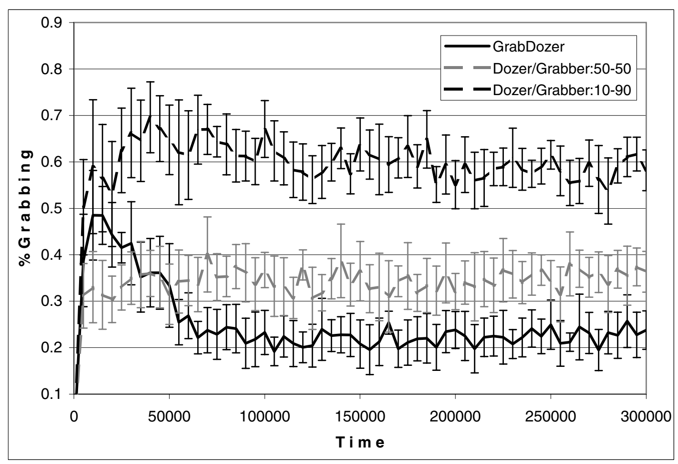


Fig. 8. Ratio of carrying agents in the fringe (5 quadrants wide) of the environment. X-axis shows time steps of experiment. Y-Axis shows number of agents that are currently carrying a particle divided by total number of agents in the fringe. Error bars are 95% confidence intervals

## V. Conclusion

In this paper, patterns created by heterogeneous populations of two types of ”specialized” agents (Grabbers and Dozers) were compared with those brought about by populations of versatile generalized agents (GrabDozers) that dynamically allocate their activities in response to changing environmental conditions. GrabDozers build similar structures in a toroidal world as a heterogeneous population composed of equal numbers of Grabbers and Dozers. However, in an enclosed environment the results differ strongly with respect to the resulting structure as well as the temporal dynamics of the building process. In the closed world experiment, no corresponding heterogeneous population composition was found that produces the same output and, at the same time, has comparable temporal dynamics as the GrabDozer population. The mixed population can produce the one-pile pattern, but only towards the end of the experiment.

This leads to the conclusion that a heterogeneous group of agents cannot be easily converted into a homogeneous population by combining the functions of the different types of specialized agents into a generalized, flexible agent. Vice versa, the dynamics of the assembly process studied by us cannot be preserved by changing homogeneous agents into a mixed population, by simply splitting the abilities into different types of agents.


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