Friends and Foes in Swarms: on Robustness of Pheromone Communication

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Abstract

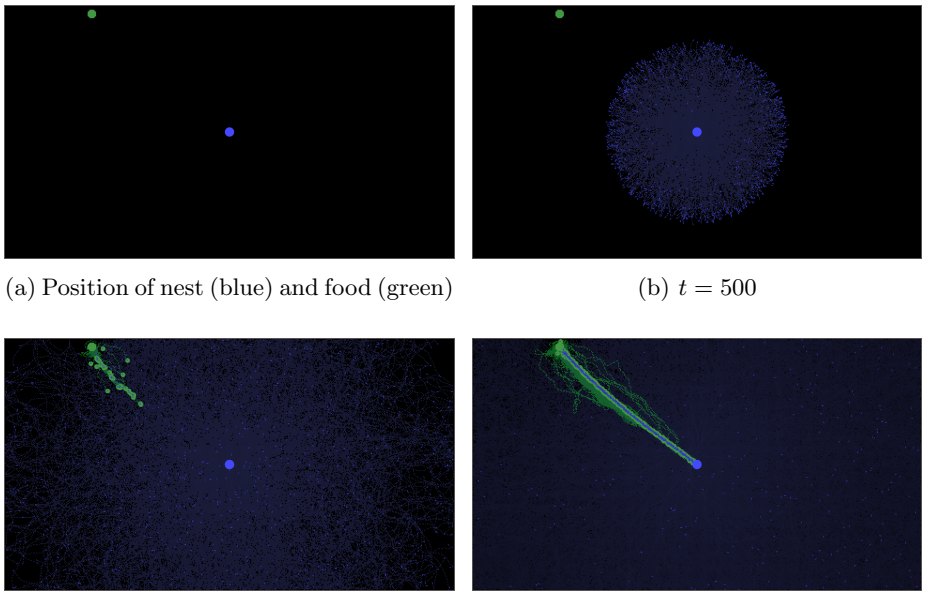
Ants use pheromone-based communication to coordinate their foraging. Communicating via the environment, known as stigmergy, is an interesting variant for controlling robot swarms without one-to-one communication. Stigmergic systems are effective but potentially vulnerable to attacks: critical information in the form of pheromones is free for detractors to read or modify. Aswale et al. [2022] researched the robustness of pheromone-based communication by introducing malicious ants to compromise the foraging colony as well as proposing a countermeasure. Their countermeasure reduces the effect of malicious ants but cannot undo it. We contribute two new scenarios, one offensive and one defensive, and compare them against the experiments by Aswale et al. [2022]. We conclude that stigmergy is prone to attacks, even if it is an effective coordination mechanism.

1 Introduction

Drawing inspiration for new technologies from nature is getting more popular in recent years. In robot swarms, robust communication between individuals is vital for effective collaboration. Mohan and Ponnambalam [2009] noticed that the behaviors of ants, bees and birds are strong influences in swarm robotic research. These animals use stigmergy, an indirect method of communication. Ants do not communicate directly with other ants but via their environment. They deploy pheromone and mark, for example, a trail between their nest and a food source. Other ants decide their next movements based on the intensity of pheromones in their vicinity. However, stigmergy can be exploited by other animals. Wyatt [2014] reports various exploits observed in nature like eavesdropping, chemical mimicry and chemical camouflage. Before pheromone-based communication can be used for autonomous robotic swarms, insight into potential attacks is needed. Aswale et al. [2022] researched the robustness of pheromone-based coordination and communication. Foundation of their research is a simulation environment with a nest and a food source. The simulation is populated with a foraging colony of cooperative ants, using *food* and *home* pheromone for communication. Malicious ants with the intent of misleading cooperative ants are introduced

to the colony. Only 3.1% malicious ants successfully prevent the foraging by deploying *misleading* pheromone, showing the fragility of stigmergy. Aswale et al. [2022] propose the use of *cautionary* pheromone as a defensive mechanism against misleading ants that can partially restore the colonies' foraging efforts. In this work, we summarize the scenarios developed by Aswale et al. [2022] and add two new scenarios: pheromone for food and cunning ants. Pheromone for food is a better performing alternative to the use of *cautionary* pheromone. Cunning ants are modified malicious ants that can switch their behavior to temporarily cooperate with the colony. In this way, they bypass the defensive mechanism of the cooperative ants.
We first describe all five used ant scenarios in Sec. 2. The results based on the effectiveness of foraging are presented and discussed in Sec. 3. Sec. 4 concludes this paper and gives an outlook for future work based on our results.

2 Ant Scenarios



(a) Position of nest (blue) and food (green)

(b) $t = 500$

(c) $t = 1,500$

(d) $t = 10,000$

Figure 1: Foraging behavior of cooperative ants at different simulation steps t: (a) The nest is located in the middle and the food source on the top left. (b) Ants start from the nest with random headings, thus spreading in a circle around the nest, leaving blue *home* pheromone. (c) The first ants found food, switched to the *to-home* mode and secrete green *food* pheromone. (d) At $t = 10,000$, the colony has established a trail between food and nest.

We evaluate five different scenarios. We start with the simple ant simulator (Sec. 2.1) which does not include malicious ants, serves as a reference and a best case scenario. The next two scenarios are the ones introduced in the original paper by Aswale et al. [2022]. They introduced malicious ants to attack the colony (Sec. 2.2) and proposed a counter measure utilizing a new type of

pheromone (Sec. 2.3). The last two scenarios are new contributions to the original paper and include a different counter measure without the need for a new pheromone type, the pheromone for food strategy (Sec. 2.4), and a new offensive tactic that can directly compete against pheromone for food (Sec. 2.5). For all scenarios, we simulate 1024 ants for $50,000$ time steps and keep the position and size of both the food source and the nest fixed. The code and simulation results are available online [1].

2.1 Simple Ant Simulator

The simple ant simulator only simulates cooperative ants that all work together with a mutual goal in mind: exploring the environment around the nest, establishing an ant trail between nest and food source and, collecting as much food as possible. To achieve this goal, the ants use pheromones. The simulated environment has a size of 1080×1920. The position of one individual ant is defined by x and y coordinates (real values with $x \in [0, 1920], y \in [0, 1080]$) and a real-valued angle $\in [0, 2\pi)$. Cooperative ants start inside the nest with random heading and in *to-food* mode. After they have found the food source, they collect food and switch to *to-home* mode. Fig. 1 displays an example of the simple ant simulation and Tab. 1 lists the parameters used for all following scenarios.

2.1.1 Simulating Pheromones

Ants can freely move in this environment, but the pheromone intensity is stored in cells of a grid overlay of size 270×480. Each grid cell can store two pheromone intensities: *food* and *home* pheromone, with values between 0 and 1000. All pheromone intensities are initialized to 0. Whenever an ant moves into a grid cell, it calculates the current pheromone intensity I as

$$I = 1000 \exp(-\lambda\tau), \tag{1}$$

with constant λ and simulation steps τ. τ is reset if an ant is in the nest or found the food source. The ant deploys a pheromone of the calculated intensity, where the pheromone type depends on the current mode: ants in *to-home* mode deploy *food* pheromone, ants in *to-food* mode *home* pheromone. In the case the cell already contains an intensity value, the maximum value is saved. Already deployed pheromone evaporates over time with a constant rate. After every simulation step, values of all pheromone types in all cells are reduced by Δt.

2.1.2 Position Update

To determine the new positions of ants for the next simulation step, each ant produces χ random vectors of lengths in $[0, l^s_{\max}]$ and angles in $[-\theta^s_{\max}, \theta^s_{\max}]$, relative to the current heading. Each vector's endpoint is evaluated in relation to the current mode: in to-home mode, ants follow *home* pheromone trails. Similarly, they follow *food* trails in *to-food* mode. The new heading θ^n is the

[1] Find the code of the ant simulator and the simulation datasets from all scenarios at https://github.com/trabbel/AntSimulator

angle of the vector with the highest pheromone intensity at its endpoint. Random noise $w \in [-\eta, \eta]$ is added to the new heading. The ants new position is calculated as

$$\theta_{new} = \theta^n + w, \tag{2}$$
$$x_{new} = x + v\cos(\theta_{new})\Delta t, \tag{3}$$
$$y_{new} = y + x\cos(\theta_{new})\Delta t. \tag{4}$$

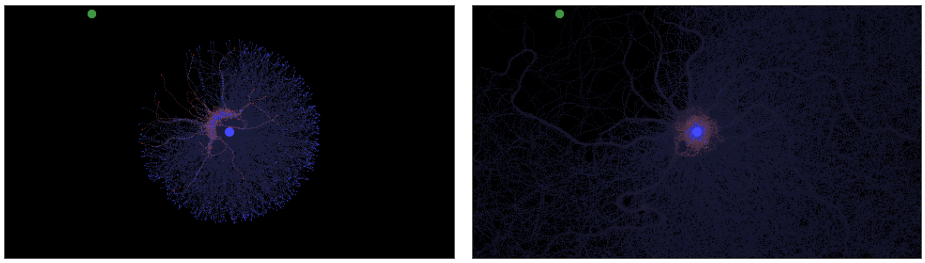
When ants reach the boundary of the simulation, food source or nest, they are reflected. Furthermore, ants do not interfere with each other except for the deployed pheromone. The number of ants inside a grid cell is unlimited.

Symbol	Value	Description
n	1024	Number of ants in simulation
N	50000	Number of simulation steps per experiment
W	1920	Simulation world width
H	1080	Simulation world height
c	4	Grid cell size
L_{food}	$(372, 36)$	Location of food source
r_{food}	16	Radius of food source
L_{nest}	$(960, 540)$	Location of nest
r_{nest}	20	Radius of nest
v	50	Ant movement per second
Δt	0.016	Time per simulation step
θ^s_{max}	0.8π	Range of vector generation for direction selection
l^s_{max}	40	Maximum magnitude of vector generation for direction selection
η	0.1π	Coefficient of random noise
λ	0.01	Coefficient for pheromone intensity
τ_{turn}	7	Simulation steps before turning
τ_{attack}	100	Simulation steps after which detractors begin to secrete *misleading* pheromone
χ	32	Number of random vectors generated for direction selection

Table 1: Parameters of the ant colony simulation, as taken from Aswale et al. [2022]. The parameters were not changed to ensure comparability between our new approaches and the original simulations.

2.2 Attacking the Colony: Malicious Ants

The approach presented by Aswale et al. [2022] introduces malicious ants to reduce the performance of foraging colonies. Malicious ants display mostly the same behavior as their cooperative counterparts with two main differences. They are always in *to-food* mode, so they always follow *food* trails, and they always deploy *misleading* pheromone instead of *food* or *home* pheromone. Ants cannot distinguish between *misleading* and *food* pheromone. While ants are in



(a) $t = 500$ (b) $t = 10,000$

Figure 2: Disruptive behavior of malicious ants at different simulation steps t: (a) As the malicious ants start directed to the food source, they distract the cooperative ants' exploration in the top left corner. (b) Over time the red *misleading* pheromone traps all ants near the colony.

to-food mode, both cooperative and malicious ants follow *misleading* trails. Malicious ants start as sleepers and only begin deploying pheromone after τ_{attack} simulation steps. They start in the nest like cooperative ants but are directed to the food source instead of starting with a random heading. The result of this attack strategy is that malicious ants shield the food source from the cooperative ants, as seen in Fig. 2. *Misleading* pheromone is restored whenever a malicious ant visits the nest (because τ resets to 0), so the concentration of *misleading* pheromone is expected to be high around the nest. Other malicious ants will only reinforce the *misleading* trails, while cooperative ants get stuck around the nest. Aswale et al. [2022] varied two parameters during their experiments: percentage of malicious ants and evaporation rate of *misleading* pheromone. They selected four parameter configurations for further analysis as seen in Tab. 2. For our following simulations, we decided to use configurations α and δ, as the other two configurations are extreme scenarios.

Configuration	*Misleading* pheromone evaporation rate	Percentage of malicious ants
α	1	3.125%
β	0	50.0%
γ	$1,000$	0.1%
δ	5	12.5%

Table 2: Configurations that Aswale et al. [2022] deemed interesting to examine further.

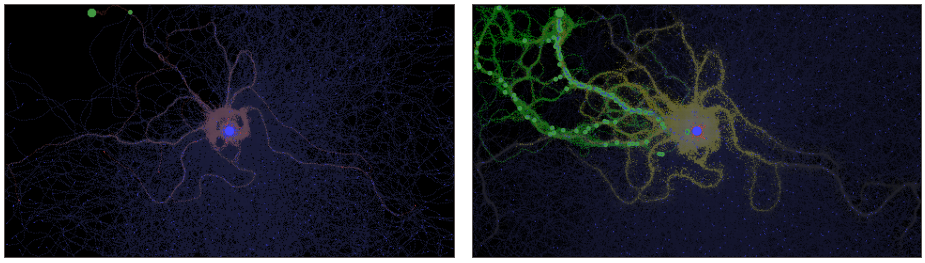
2.3 Defending the Colony: Cautionary Pheromone

To defend the colony against the malicious ants introduced in Sec. 2.2, Aswale et al. [2022] added a third type of pheromone: *cautionary* pheromone as a mechanism to counter the *misleading* pheromone laid out by malicious ants. *Cautionary* pheromone intensity is saved in the grid cells and evaporates like *food* and *home* pheromone, but deployment and usage during foraging differs. It is only deployed by cooperative ants in *to-food* mode, where the intensity is

calculated as

$$I = 1000 \exp(-\lambda p) \tag{5}$$

and depends on the patience p with $p \in [0, p_{\max}]$. In contrast to the calculation of the other pheromone intensities in Sec. 2.1.1, p is initialized as $p_{\max}$ and decreases. While *food* and *home* pheromone get weaker over time, *cautionary* pheromone gets stronger. p is reset to $p_{\max}$ when the ant finds food and is increasing with t_p per simulation step if the ant does not follow a *food* trail.
The movement of ants follows similar rules as in Sec. 2.1.2: a number of random vectors is generated and the one with the highest pheromone intensity is chosen for the new heading. The only difference is that all vectors where the intensity of *cautionary* pheromone is stronger than the intensity of *food* pheromone are discarded. The result of this defense is that the malicious ants lock the cooperative ants up at the nest in the beginning, but that the cooperative ants deploy higher and higher intensities of *cautionary* pheromone, until they can break free and start foraging (see Fig. 3). Aswale et al. [2022] tested different combinations of t_p and $p_{\max}$. They found the best performance of this defensive strategy with $t_p = 2$ and $p_{\max} = 250$. We use these values for our evaluation later.

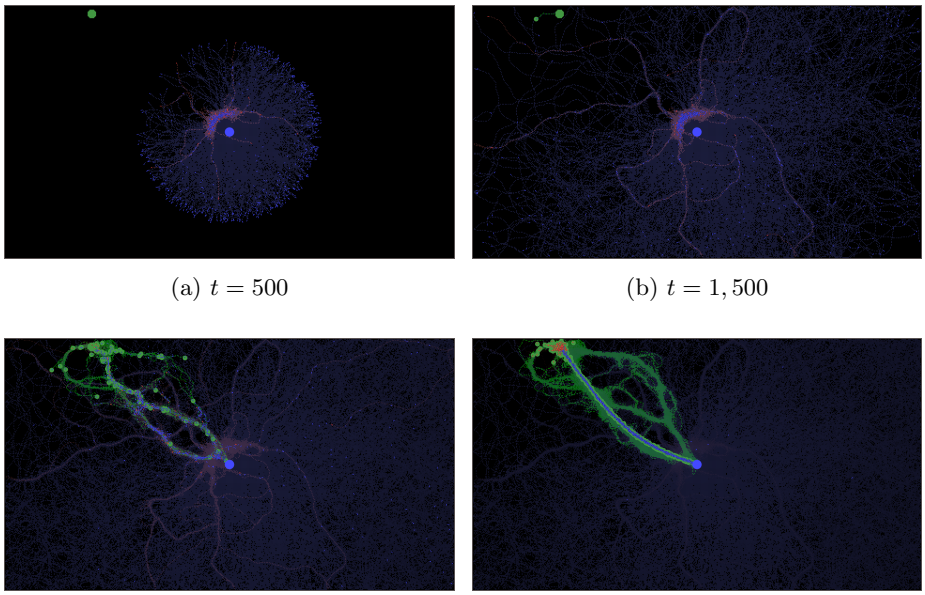


(a) $t = 1,500$ (b) $t = 10,000$

Figure 3: Effect of *cautionary* pheromone at different simulation steps t: (a) Relatively early into the simulation, malicious ants successfully distract the cooperative ants. In this stage, red trails of *misleading* pheromone around the nest are noticeable. (b) The yellow *cautionary* pheromone secreted by cooperative ants gets stronger over time, until it covers the *misleading* trails. Cooperative ants can find a way to the food source, even though it is not as efficient as without malicious ants (see Fig. 1).

2.4 Defending the Colony: Pheromone for Food

We propose another defensive mechanism against malicious ants as our own contribution: the pheromone for food strategy. It is an alternative to the introduction of a third type of pheromone as in Sec. 2.3 and changes the conditions for resetting τ. It is therefore modifying the capability to deploy high-intensity pheromones. Cooperative and malicious ants do not get an automatic refill whenever they arrive at the nest, but only if they actually deliver food. This condition does not change much about the cooperative ants' behavior because it aligns with their goal. But the success of malicious ants is based on a specific strategy: locking the cooperative ants near the nest with high intensities and a high concentration of *misleading* pheromone. Even if the *misleading* pheromone



(a) $t = 500$ (b) $t = 1,500$

(c) $t = 5,000$ (d) $t = 10,000$

Figure 4: Defensive pheromone for food strategy at different simulation steps t: In the beginning, the colony behaves just like a colony without any defensive strategy: malicious ants prevent the exploration of the top left corner (a) and start locking cooperative ants near the nest (b). After the *misleading* pheromone sufficiently evaporated, cooperative ants can continue their exploration (c) and establish a trail between food and nest (d).

evaporates, malicious ants are likely to randomly reach the nest, reset τ and again deploy *misleading* pheromone of high intensity. This is no longer possible if they do not collect food before they return to the nest. An example of this new behavior is shown in Fig. 4.

2.5 Attacking the Colony: Cunning Ants

We contribute also a modification of the malicious ants to make the pheromone for food scenario described in Sec. 2.4 more interesting. So far the malicious ants only had one mode of operation: searching *to-food* trails and secreting *misleading* pheromone. Even in the simple ant simulator without malicious ants (see Sec. 2.1) the cooperative ants switched regularly between two modes. To overcome the pheromone for food strategy, the malicious ants have to cooperate at least a bit to refill their pheromone. We introduce an additional routine, transforming the malicious, but 'basic' ants into cunning ants that can change their behavior. Cunning ants first behave like malicious ants, but actively search for food and deliver it to the nest if their pheromone intensity gets weak. For simplicity of simulation, we do not directly implement a threshold for the intensity, but for τ. If this threshold ε is exceeded, the ant behaves like a cooperative ant, searches for food and delivers it to the nest, where the ant changes again to its cunning behavior. We investigate the influence of different thresholds and

use $\varepsilon \in \{25, 50, 100, 200, 300, 400, 500, 600\}$.

3 Evaluation

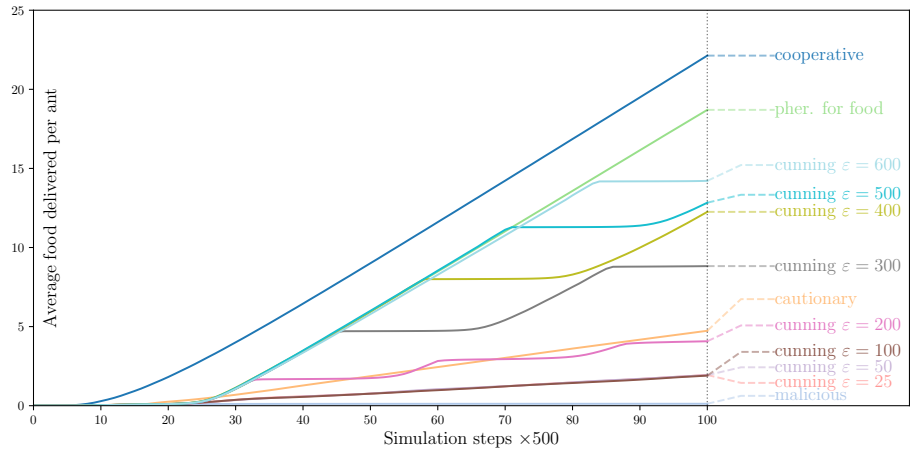


Figure 5: Average food delivered per ant with configuration α. All twelve data lines are averaged over 100 individual simulations each. The plot is cumulative and always displays the amount of collected food from the start of the simulation.

To evaluate the five different scenarios, we choose the average number of collected and delivered food per ant as main measure. For $50,000$ simulation steps, we log the average number of collected and delivered food every 500 steps. The five ant scenarios lead to twelve experiments (only cooperative ants, malicious ants but no counter strategy, *cautionary* pheromone, pheromone for food, eight different ε for cunning ants) and each experiment is done for parameter configurations α and δ (see Tab. 2). To not only rely on one simulation, all scenarios are simulated 100 times and the resulting dataset is averaged over the 100 simulation runs. In total we ran $12 \cdot 2 \cdot 100 = 2,400$ simulations with $50,000$ steps each.
Fig. 5 contains results of experiments with α configuration (malicious ants: 3.1%, *misleading* pheromone evaporation rate: 1), Fig. 6 the results with δ configuration (malicious ants: 12.5%, *misleading* pheromone evaporation rate: 5). First, we want to confirm the results of Aswale et al. [2022]. We compare the plots without malicious ants, with malicious ants but without any countermeasure and with malicious ants and *cautionary* pheromone. With only cooperative ants, the delivered food increases linearly over time after a short delay after the start. The ants need approximately $5,000$ simulation steps to establish a trail between food source and nest. If malicious ants are added, the number of delivered food drops to zero for both configurations, showing the drastic effect of as few as 3.1% respective 12.5% malicious ants. If the colony defends itself using *cautionary* pheromone, again a linear increase after a delay is visible, but the increase is less steep than without malicious ants. A comparison between only cooperative ants and a cautionary colony with malicious ants shows

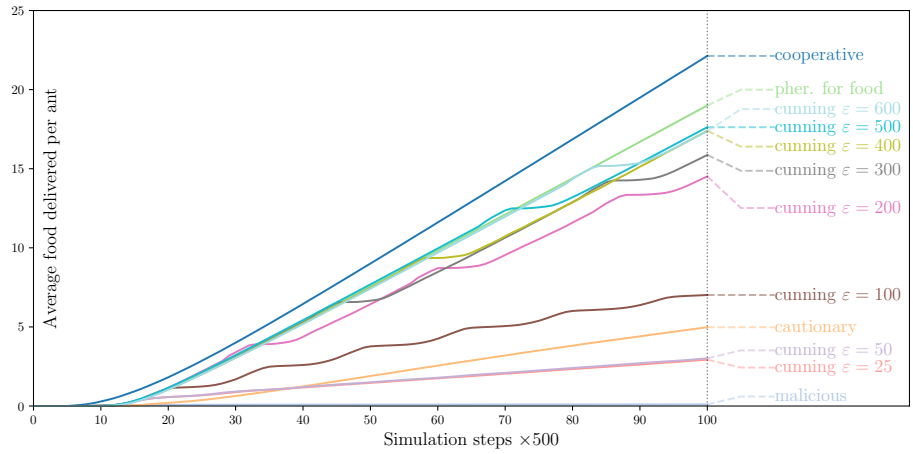


Figure 6: Average food delivered per ant with configuration δ. All twelve data lines are averaged over 100 individual simulations each. The plot is cumulative and always displays the amount of collected food from the start of the simulation.

that *cautionary* pheromone can only restore less than one quarter of the initial performance. The simulations confirm the results of Aswale et al. [2022].
Now we are interested in the performance of our contributions, pheromone for food and cunning ants. Pheromone for food turns out to be a more effective defensive strategy than using a *cautionary* pheromone. Comparing the result after $50,000$ simulation steps, pheromone for food reaches approximately 80% performance of the cooperative colony. This is also the first time that differences between the parameter configurations are visible: α needs more time to overcome the *misleading* pheromone but shows a steeper increase afterwards, nearly parallel to the cooperative colony. The delay in the beginning depends on the evaporation rate. For δ, *misleading* pheromone evaporates five times as fast as for α, so the colony can overcome *misleading* trails faster. After the food source has been found, all cooperative ants collect food, however, a few percent of the total number of ants are now malicious and do not forage. The performance is based on the average food delivered per ant, not per cooperative ant. This explains the difference in slopes: α has a lower percentage of malicious ants than δ, thus the α slope is steeper.
Depending on ε, cunning ants show two behaviors: for bigger values of ε ($\varepsilon \geq 200$ for α, $\varepsilon \geq 100$ for δ) a linear increase, interrupted by stagnating parts is visible. See Fig. 6 as example: with a threshold $\varepsilon = 200$ four segments of nearly linear increase are visible, as well as three segments without increase in between and one delay in the beginning. This shows the switching behavior of cunning ants. The first delay is the time needed to overcome the malicious pheromone secreted in the beginning of the simulation. After *misleading* pheromone sufficiently evaporated, we can observe a linear increase. So far the line follows the pheromone for food data. Using again $\varepsilon = 200$ in Fig. 6 as example, we can see the first non-increasing range at approximately $16,000$ simulation steps and also a short time span before where the performance exceeds the pheromone for food strategy. The reason for the short duration of higher performance is

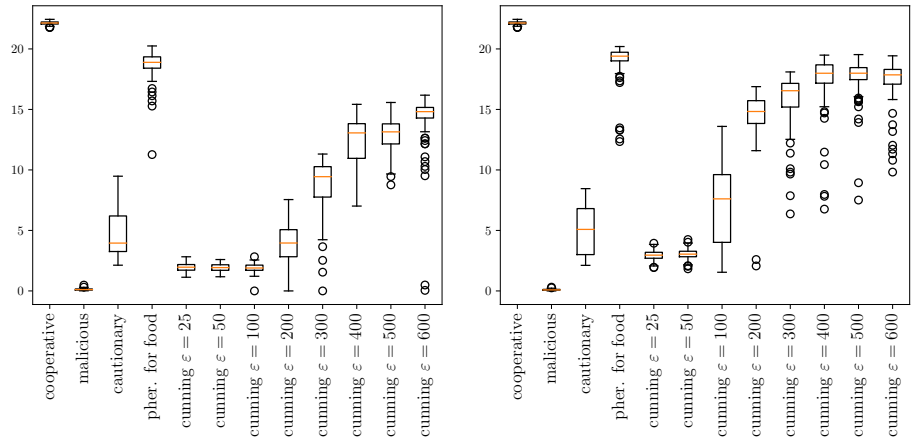
that cunning ants have to deliver food to refill their pheromone, so after the threshold is exceeded, they follow the trail back to the nest and deliver food, exactly like cooperative ants. This behavior cannot be seen with pheromone for food because malicious ants do not have a reason to help with the foraging task of the colony. After the cunning ants successfully delivered food and reset their counter, they start again to secrete high-intensity *misleading* pheromone and lock the cooperative ants near the nest. The colony alternates between these two phases of successfully foraging and being locked at the colony; the rate of alternating depends on the chosen threshold.

The second behavior affects lower values of ε ($\varepsilon \leq 100$ for α, $\varepsilon \leq 50$ for δ). Figs 5 and 6 display that these lines are plotted over each other and do not show the alternating behavior, only a relatively weak linear increase. Lowering the threshold even further therefore has no effect on the colony because the ants need a minimum amount of time to establish a trail between food and nest after they overcame the *misleading* pheromone. Cunning ants also are dependant on this trail to find food that they have to deliver for pheromone refilling. Even if they switch early to *to-food* mode, they have to wait for the cooperative ants to find the food source. A low threshold also means that a cunning ant immediately returns to the nest after it found food, while a high threshold means that cunning ants wait until the threshold is exceeded. Thus gathering together at the food source and than returning all together to the nest. This difference is the reason why we cannot see steps in the plots, but only a linear increase.

Comparing α and δ we can conclude that the foraging performance with cunning ants is higher for δ. The evaporation rate is a bigger factor than the percentage of cunning ants, because the higher evaporation rate of δ experiments allows the colony to overcome the *misleading* pheromone faster. While this does not make a big difference for pheromone for food (without cunning ants), it is a strong influence for the cunning ant scenarios because the cooperative ants do not have to overcome the *misleading* pheromone once in the beginning but repeatedly.

Figs. 5 and 6 use averages of 100 experiments each. To investigate the variance between experiments, we show box plots of both configurations in Fig. 7. The results are as expected: only cooperative ants, malicious ants without any countermeasure, or thresholds that were the lower bound in Figs. 5 and 6 have a low variance and few outliers. The other, more complex behaviours, have a higher variance and more outliers.

Furthermore, we perform a Wilcoxon signed-rank test introduced by Wilcoxon [1945] to test whether the different plots belong to different distributions. We calculated the p-values for every binary combination of scenarios inside the same parameter configuration. As input the last collected values at simulation step $50,000$ of all 100 experiment iterations are used. If $p < 0.01$, we assume that there are differences between the two tested scenarios and our results are statistically significant. For both configurations α and δ we performed 66 tests each, Tab. 3 displays the nine scenario combinations with $p > 0.01$, the other 123 tests resulted in p-values smaller than 0.01. As expected, any combination of lower bound thresholds ($\varepsilon \leq 100$ for α, $\varepsilon \leq 50$ for δ) results in a high p-value because a change of ε does not change the colony behavior anymore. The other combinations with high p-values show a possible connection between the scenarios, but are only a result of the limited simulation time. See Fig. 6 as example: thresholds $\varepsilon \in \{400, 500, 600\}$ result in similar values after $50,000$ simulation steps.



(a) α (b) δ

Figure 7: Box plots of all twelve scenarios for configuration α (a) and δ (b).

Configuration	Data set a	Data set b	p-value
α	cunning $\varepsilon = 200$	cautionary	0.017
α	cunning $\varepsilon = 400$	cunning $\varepsilon = 500$	0.146
α	cunning $\varepsilon = 50$	cunning $\varepsilon = 100$	0.458
α	cunning $\varepsilon = 25$	cunning $\varepsilon = 100$	0.721
α	cunning$\varepsilon = 25$	cunning $\varepsilon = 50$	0.739
δ	cunning $\varepsilon = 25$	cunning $\varepsilon = 50$	0.132
δ	cunning$\varepsilon = 500$	cunning $\varepsilon = 600$	0.227
δ	cunning $\varepsilon = 400$	cunning $\varepsilon = 600$	0.286
δ	cunning $\varepsilon = 400$	cunning $\varepsilon = 500$	0.925

Table 3: Binary combinations of scenarios with p-values higher than 0.01.

These thresholds take a long time until the malicious ants again successfully prevent foraging. Longer simulations would make the differences visible.

3.1 Discussion

Aswale et al. [2022] work with some assumptions that are not properly explained. To keep this work and our contributions comparable to the original paper, these assumptions were not changed but are still worth mentioning. As seen in Fig. 2, malicious ants can effectively shield the food source from the nest using *misleading* pheromone, despite their low numbers. In contrast to cooperative ants they started oriented to the food source, while their cooperative counterparts start with a random heading. This allows the malicious ants to perform a concentrated attack and greatly improves their effectiveness. Why should malicious ants have this advantage?

Another question concerns the secretion of pheromone. When an ant deploys pheromone in a cell that already contains pheromone of the same type, the intensities are not added together, but only the maximum intensity is saved. It does not matter how many ants deposit high-intensity pheromone in a cell, the

intensity can never exceed the maximum of $1,000$, but why should a cell have this arbitrary limit?
The general idea of this ant simulation is to generate complex behaviors with as simple as possible individuals. The proposed counter strategy of *cautionary* pheromone is in our opinion a relatively big change because of the addition of a third type of pheromone.
Finally, we can probably always find a new behavior that is an efficient attack strategy against the current colony. Vice versa we can probably also always find a new defensive countermeasure against the new attack. Where should we end with hard-coded behaviors? It would be more interesting to see how both sides would perform in an evolutionary arms race, but that would go beyond the limitations of this work.

4 Conclusion

In this work we explored the usage of pheromones for foraging in a simulated ant colony. Ants scout their environment and form trails of two different pheromone types to navigate between their nest and the food source. Aswale et al. [2022] demonstrated that a small percentage of malicious ants of 3.1% is effective in locking cooperative ants close to the nest, thus preventing nearly all food collection. These detractors secrete *misleading* pheromone and fake *to-food* trails so that the colony is distracted from the food source. Through the introduction of a third type of pheromone, cooperative ants were able to counter the efforts of malicious ants and reestablished their trails. This new *cautionary* pheromone warns other cooperative ants against possible *misleading* trails. However, the colony could only reach a performance of approximately 22% in comparison to a colony without malicious ants. Pheromone-based cooperation approaches prove to be effective for exploring and foraging, but also provide easy starting points for manipulations.
We contributed two new strategies: the pheromone for food strategy as an alternative to *cautionary* pheromone to defend the colony and cunning ants as a more intelligent variation of malicious ants. Pheromone for food tries to prevent malicious ants from refilling their pheromone: in the original simulation, pheromones of both malicious and cooperative ants are always refilled when they arrive at the nest. Now ants only receive pheromone in exchange for collected food. Since malicious ants can no longer secrete a near infinite amount of *misleading* pheromone with high intensity, the colony quickly overcomes their trap and performs with 80% effectiveness. Our new defensive mechanism was not only more efficient than *cautionary* pheromone but also a smaller intervention in the simulated ecosystem because we did not need a completely new type of pheromone.
Cunning ants are able to react to the change of pheromone for food: after their pheromone supply undercuts a threshold, they temporarily switch from their destructive behavior to cooperative behavior until they found food and exchanged it for new pheromone. We experimented with different thresholds and were able to greatly reduce the performance of the colony (9% for α, 13% for δ). Nevertheless, cunning ants can not completely prevent foraging since they periodically have to allow the colony to find the food source.
Even with different approaches we come to the same conclusion as Aswale et al.

[2022]: while pheromone-based coordination is an effective and simple swarm communication method, it is fragile and easy to exploit.

4.1 Future Work

Even the simple ant simulator without any detractors is a complex system with many different parameters (see Tab. 1). Adding two attack and two defense strategies only raises the number of different configurations so that many more experiments are conceivable: changing the total number of ants or the percentage of malicious ants, using multiple food sources or multiple nests, trying different combinations of pheromone evaporation rates, just to name a few. Additionally, we noticed some interesting assumptions in Sec. 3.1, like the orientated initial heading of malicious ants in contrast to the random heading of the cooperative ants. Giving both groups a random or both an orientated initial heading could change the general dynamic and may be interesting to test. Finally other offensive and defensive strategies can be examined. These new strategies are not only limited to hard-coded strategies like presented in this paper, but can also include meta strategies to choose an appropriate behavior from a pool of simpler strategies or even evolutionary approaches.

References

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