Neozoa: An Immersive, Interactive Sandbox for the Study of Competing Ant Species

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ABSTRACT

In this paper, we present an interactive simulation game with the objective to understand the mutual interferences of competitive (ant) species by experiencing their behaviour in a novel way. To reach that goal, the simulation makes use of current virtual reality devices (specifically the Oculus Rift DK2) to increase the level of immersion for the user. The focus of our research lies on the design and simulation of the foraging strategies of two antagonistic ant species, as well as the creation of an accessible experimentation environment. In particular, an invasive species based on the Argentine Ant (*Lipethima Humile*) is introduced into an ecosystem already populated by a native species modelled along the Black Garden Ant (*Lasius Niger*). The user can then use virtual tools inspired by real-life means to control the spreading of ants and help the native species to survive despite being inferior to the invasive ant. Options include manipulating pheromones used by the ants for navigation and, thereby, influencing the mechanism of mutual identification, or placing obstacles that block the ants' path. Also, many key parameters that control the ants can be modified during runtime. An integrated logging mechanism allows to collect data which can be processed by standard tools. The simulation also offers a dynamic, nature-inspired interactive example of the Ant Colony Optimization principle and can help to make natural processes more accessible.

Keywords: Virtual Reality, Sandbox, Education, Ant Algorithms, Self-Organisation, Optimisation.

Index Terms: H.5.1 [Information interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information interfaces and Presentation]: User Interfaces —Graphical user interfaces G.1.6 [Mathematics of Computing]: Optimization—Ant Colony Optimization

1 INTRODUCTION

The introduction of a new species on foreign ground can have massive impact on the environment including the extinction of existing native species [17]. Only when a species can sustain and increase its own population in the new area without human intervention (i.e. supply of specimen from native habitats to foreign grounds, e.g. through trade), and subsequently spread significantly beyond the introduction site, it is considered *invasive*. As one of the most dangerous, the Argentine Ant (*Lipethima Humile*) is in the Top 100 List of the World's Worst Invasive Alien Species, published by the *Invasive Species Specialist Group (ISSG)*, which aims to reduce threats to natural ecosystems and their native species by raising awareness about invasive alien species and ways of prevention [14]. The spread of species can be linked directly to human intervention, especially the increase of global trade. Argentine Ants are brown coloured, and were originally only located in South America. As of today, the it has spread to six continents and several ocean islands with the help of human transportation [23]. Argentine Ants are reported to be more successful in food harvesting than other ant species. The introduction of the Argentine Ant can have severe negative effects on native ant diversity [5]. Being a dominant territorial ant, *L. Humile* typically displaces native ants, given a sufficiently habitable environment [15]. An example for the negative impact on native flora can be found in [11], where the natural process of seed distribution was nearly completely interrupted by the dominance of *L. Humile* ($> 90\%$) in invaded areas. The effects on anthropod populations in Hawaii was studied in [6], finding severe reduction in both predators and pollonators of native plants, while some other non-native insects species were found to become more abundant. Furthermore, [22] provides a direct link between the occurrence of the Argentine Ant and declining population numbers of vertebrates, specifically horned lizards in California. A wide range of impacts of *L. Humile* on humans can be observed. Intense spread around residences affects rural areas [12]. The presence of the Argentine Ant harms natural predators, leading to the spread of mites, who in turn negatively affect crop yields [13].

In this work, we present an interactive simulation of two ant species in a dynamic environment, competing for predominance. At the core of our work lays a modular ant agent model, which can be configured and customized by various control parameters, such as motion, foraging and combat behaviour. In addition, it includes pheromone-based navigation behaviour that approximates real ants and can be modified during runtime in an interactive simulation. A logging mechanism allows the creation of meaningful data sets to compare foraging performance of different configurations. Based on this model, the competition about predominance between two ant species with different parameters can be simulated. This is further extended and gamified into a round-based game. In each round, the species compete for a limited amount of time in a world with limited resources. We further exploit the use of a Head Mounted Display (HMD) to increase user immersion and explore the possibilities of Virtual Reality Applications. Virtual Reality Applications have been classified as *disruptive technologies* for education, as they continue to exhibit strong motivational effects beyond pure novelty which can be attributed to high amounts of user immersion [20]. Virtual 3D environments "provide the possibility of rich learner engagement, together with the ability to explore, construct and manipulate virtual objects, structures and metaphorical representations of ideas" [8]. After abstracting the natural process and selecting only the relevant feature set to represent it, the graphical visualization in combination with an HMD aids in making exploration intuitive. For example, after visually assessing the broader interactions between the ants, the user should be able to apply natural skills to inspect a localized feature in more detail: Using his ability to physically move closer.

In Section 2.1, we provide related works on ants, in particular the Argentine Ant. The concept for the simulation and its gamification, which includes the users perception and interaction, is part of Section 3. Section 4 describes the simulation model of the ants and the ecosystem as a whole. In Section 5, mechanisms for data logging and visualization are shown. Section 6 presents the results of preliminary evaluation of our work. Finally, in Section 7 we briefly

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hint at possible improvements and extensions for our simulation in future works.

2 Related Work

In this section, we will give a short introduction to virtual reality and education, present examples of interactive ant simulations and elaborate on the scientific basis for the aspects underlying our work.

2.1 Virtual Reality in an Educational Context

In [8], a categorization of characteristics of 3D virtual learning environments (VE) is proposed, which distinguishes between aspects of *representational fidelity*, including realistic, consistent and smooth display of the environment, especially motion, and *learner interaction*, which includes embodied actions (view control, navigation, object manipulation) and control of environment attributes and behaviour. They further identified several affordances that facilitate learning tasks for VEs. These include tasks that lead to the development of enhanced spatial knowledge representation of the explored domain, experiential learning tasks that would be impractical or impossible to undertake in the real world, and learning tasks that lead to increased intrinsic motivation and engagement.

2.2 Existing Ant Simulations

Several simulations of ant behaviour have been published. An example for a comprehensive ant colony simulator can be found in *Myrmedrome* [4], which incorporates different aspects of pheromone based communication beyond foraging and a dynamic environment. Being the inspiration for the Ant Colony Optimization principle, examples for agent-based implementations can be found in popular multi-agent frameworks, e.g. *NetLogo* [27]. The programming learning suite *AntMe!* [26] uses ants and agent-based concepts, as well as pheromone-based communication, to intuitively teach programming, also sporting a 3D graphical representation. Our work focuses on the pheromone-based navigation, a recognition mechanism based on bit pattern matching, means of interaction in a 3D environment using tools modelled along real-life counterparts, and integration with virtual reality gear to increase immersion and thereby improve the user experience.

2.3 Pheromone-Based Navigation of Ants and the Concept of Ant Colony Optimization

To communicate and locate food sources, ants secrete pheromones to indicate paths to food sources [18]. These trail pheromones persist for some amount of time (*L. Niger*: $\varnothing 0.75h$ [2]) but evaporate continuously. The dynamics of evaporation of pheromones and the spread of new pheromones by food-carrying ants leads to an interesting effect. Assume there are two possible paths of unequal length between the nest and a food source, and ants choose randomly which path to take. Due to the shorter time ants spend travelling the more direct path, the amount of pheromones will grow more rapidly on the shorter compared to the longer path. Taking into account that ants prefer to navigate towards higher concentrations of pheromones, the amount of ants on this path makes it more attractive, thereby creating a positive feedback loop [3]. Pheromone-based navigation represents a decentralized method to find shortest paths in complex environments. This indirect way of transporting information by manipulating the environment in a local way is also called *stigmergy*. Inspired by these findings, a heuristic approach to complex optimization problems called *Ant Colony Optimization* (ACO), for example the travelling salesman problem [21], was proposed by Dorigo et al. and has continuously evolved since then into its own area of research [9]. Using an agent-based probabilistic approach to explore the solution space, the principle of pheromone-based navigation is used to find optimal solutions in an iterative approach. It has proven its effectiveness and found numerous applications. Furthermore, users can refer to a multitude of theoretical results. Besides pheromone trails, visual landmarks may help the ants with navigation [10]. It is known that ants can count their steps in relation to the angle of the sun, allowing them to asses the distance and relative position of the nest, a mechanism called *Path Integration* [7]. Some pheromones ants use for trail marking have been synthesized and trails manipulated successfully [1].

2.4 Recognition Mechanics

Ants can use a pattern matching mechanism based on a chemical “fingerprint” of hydrocarbons in their shell to identify other ants’ tribal membership. The specific match-finding works on an “overall similarity” between two ants’ signature [19]. It has been shown that this mechanism can be disturbed by the application of synthesized hydrocarbons, driving ants towards hostile behaviour within their own tribe, while being relatively harmless to other species [25]. Furthermore, so-called crematoenones were discovered [16]. This substance class “weakens” the hydrocarbon pattern and, thereby, reduces the interspecific aggressiveness of the ants. This helps parabiotic species, two ant species which are living together in the same nest but do not share the brood, to cohabitate.

3 Interactive Simulation and Gamification Concept

To give the user control over the model parameters, a graphical user interface is available to globally control many aspects of the ants, concerning foraging behaviour, pheromone navigation, motion and combat during runtime. This allows to study the impact of e.g. the amount of pheromones spread when carrying food on the formation of trails in real time. As an indirect means of interaction, pheromone trails can be manipulated in first-person perspective by adding or removing pheromones. Furthermore, the user can obstruct the motion of the ants by placing obstacles, which forces the ants to find different routes. To encourage the user to further explore the simulation, a round-based concept was chosen, where the user has to help the native ants survive for as many rounds as possible.

3.1 Environment and Visualisation

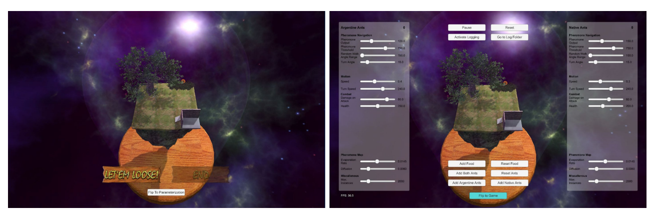

Figure 1: The game view (left) allows the user to start or end the game. The parameterization view (right) allows to extensively configure the ants behaviour as well as to add and manipulate food sources, and spawn additional ants.

Being rendered in full 3D, the agents act on a 2D area of $15m \times 15m$ size (Figure 2). The player can move around freely. The application sports two views. The exterior view provides the user with the game control and the model parameterization screen, through which ants can be further configured. These give an overview and allow the modification of the current model parameters (Figure 1, right). In first-person view, the user can explore the game world and interact with the ants directly. View augmentations (Figure 3) can be activated, visualizing ants, pheromone trails and food sources prominently in both views.

3.2 Virtual Reality Head Mounted Display

Neozoa’s interactive mode is optimised for the utilisation of a Virtual Reality Head-Mounted Display (HMDs) such as the Oculus Rift DK2. The resulting view, which is both stereoscopic and

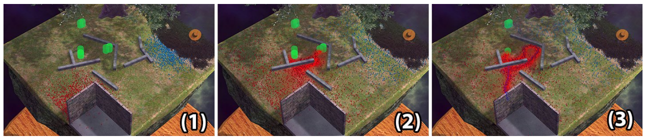

Figure 2: The virtual environment of the simulation. Walls can be placed by the user to block ant paths. Optional augmentation is given in form of blue and red markers to localize ants as well as an overlay showing pheromone concentration. From left to right, the process of path finding can be seen. (1) First, the ants roam randomly. (2) Upon encounter with a food source, pheromones will be spread during the return to the hive. (3) After some time, higher pheromone concentrations form on shorter paths.

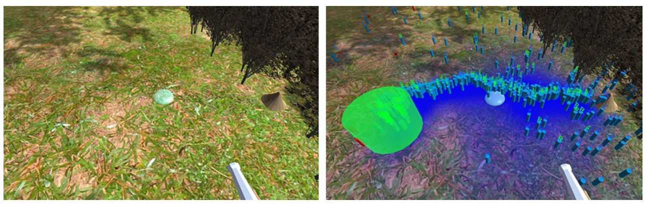

Figure 3: Standard and augmented view in the game. In addition to mere mesh displays (left), red and blue markers show the tribal membership of ants. Small letters indicate the current state of individuals (**S**earching, **R**eturning, **C**ombating). The blended colour overlays depict pheromone levels. Food sources are visualized by green cylinders.

adjusted to the users head-orientation in combination with full gamepad control enhances the user immersion. Wearing the HMD, the user can look around freely and limited movement within the frustum of the Oculus Position Tracker is possible, especially kneeling down to inspect ant behaviour more closely. Longer ranged spatial motion is realized in a "Tank-like" fashion, where heading is controlled via a thumbstick, but can be synchronized with the viewing direction by pressing down the stick. Object selection and action execution are realised by (1) pointing the head at the intended target, e.g. a virtual tool on a shelf, or a point where a tool should be effected, and (2) triggered by pressing a specific button on the gamepad.

3.3 Interaction with Ants

The configuration screen allows the user to manipulate all relevant model variables for each species separately, such as pheromone output and evaporation rate, speed, or health, and to spawn ants of each species on demand. In addition to the general parameter configuration, the user can directly shape and modify the ant's environment through the manipulation of food sources, the creation of walls, and especially using modalities modelled closely along the means of insect control mentioned in Section 2.1. The latter can be applied in a first-person view as shown in figure 4. Each of these is represented by a virtual tool and controlled by a gamepad and the players viewing direction. Using the *Water Hose* (here, other substances would be more suitable in real-life applications, see [24]), the amount of pheromones of both native and Argentine Ants can be decreased locally. With the *Synthetic Pheromone Dispenser*, the user can lay pheromone trails to distract or help the ants. The *Hydrocarbon Dispenser* allows to modify the smell emitted by some ants, disturbing their identification mechanism and raising the chances of intra-tribal attacks. Furthermore, the user can deploy and manipulate bricks which act as obstacles to the ants and thus further experiment with the path finding and pheromone trail system.

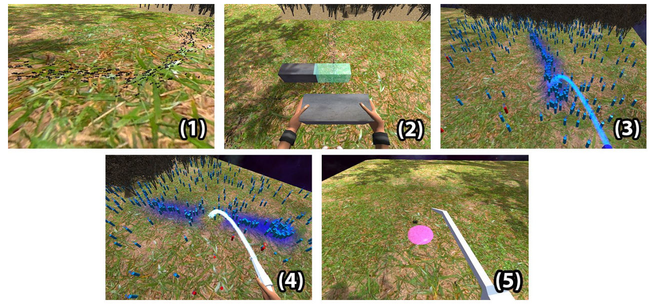

Figure 4: Interaction with ants, first-person: (1) Kneeling to inspect ant trails, (2) laying bricks to force the development of complex paths, (3) using synthetic trail pheromones to lead ants, (4) removing pheromones using a water hose, (5) applying synthetic hydrocarbons to disturb identification mechanisms

3.4 Game Mechanics

The game is round-based, each round lasts ten minutes. This allows the simulated ants the exploitation of both close and more remote food sources. The game ends when the native population count reaches zero. The key configuration of each round consists of *(1) the number of ants to spawn* per tribe at the beginning, *(2) the amount of food* available to the ants, distributed randomly and required by the ants to procreate, and *(3) the number of birds* who prey on the ants. For every round, the amount of food as well as the number of birds is set randomly. Beginning with the second round, the number of ants to spawn equals the number of surviving ants from the preceding round. The native ants should experience favourable conditions and survive for some time without any intervention by the player, but the Argentine Ant pose a direct threat to each individual ants survival as well as a competitor in the race for food, reducing the species capability to procreate and balance the losses through bird attacks.

4 The Underlying Model

In this section, the adoption of the scientific basis described in Section 2.1 and its implementation will be presented. All ants in our simulation as well as the birds and the food sources are implemented as autonomous agents. The ant species share the same implementation with different parameters (see Table 1). Birds use a simple flocking model for motion and prey randomly on ants. The Argentine Ant is slightly bigger, moves faster, effects more damage on attack and has better health than the black native ant.

4.1 State-Control

Each ant has three possible states: *Combating*, *Searching* and *Returning*. The correlations and transitions are shown in Figure 5. Ants are instantiated in *Searching* state. Upon arrival at a food source, they remove some amount of food, as defined by the food source, and change their state to *Returning*. On the way home, ants secrete pheromones to indicate a path to the food source to other ants. As soon as they arrive, the food is deployed and the state is changed back to *Searching*. The state *Combating* is activated if the ant collides with another ant and recognizes it as hostile (Section 4.3), or when it is attacked by another ant. If the ant loses the fight, it dies and is removed from the simulation. Otherwise, it returns to its former state.

4.2 Navigation And Pheromone Maps

In our simulation the ants' navigation system relies on artificial pheromones and landmarks, see Section 2.3. The pheromone navigation behaviour is built upon a simple motion control, which offers basic waypoint-based navigation and obstacle avoidance.

Table 1: Parameter Comparison of the Default Agent Configurations. Differences between species are highlighted.

Parameter	Native	Argentine
Pheromone Navigation		
Pheromone Output (s^{-1})	**150**	**110**
Pheromone Threshold	750	750
Turn Angle (°)	15	15
Motion		
Random Walk Angular Range (°)	165	165
Speed (ms^{-1})	**0.32**	**0.40**
Turn Speed ($°s^{-1}$)	120	120
Attack and Identification		
Attack Damage	**60**	**80**
Health	**200**	**250**
Smell Pattern	**b11110000**	**b00001111**
Pheormone Map		
Pheromone Evaporation Rate (s^{-1})	0.016	0.016
Pheromone Diffusion Rate (s^{-1})	0.006	0.006
Pheromone Maximum Value	2000	2000

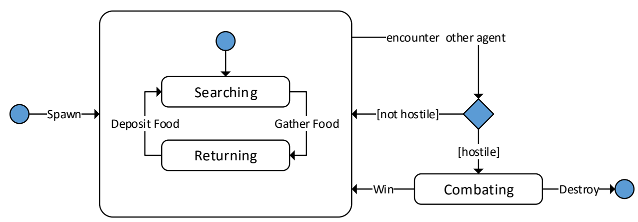

Figure 5: State diagram of an ant agent. During their lifetime, ants mainly alternate between *Searching* and *Returning*. In case of an encounter with a hostile ant, transition to *Combat* state is made. Upon victory, the agent returns to the previous state. Otherwise, it dies and is removed from the simulation.

The navigation of food-searching ants is based on a pheromone system. For this, the terrain is mapped onto two pheromone maps, one for each species, implemented as 2-dimensional arrays. Each entry in the array stores the pheromone concentration for a the corresponding rectangular area (cell) on the map, which is influenced by ants carrying food as well as by evaporation and diffusion. Diffusion spreads a small fraction of each cell to its Moore neighbourhood, while evaporation simply reduces the concentration by a relative amount per second (see Table 1). The minimum value for each cell is zero, the maximum value is configurable. Ants of one species ignore and have no influence on other species' maps. To mark its path to a food source, an ant carrying food constantly spreads pheromones until it arrives back at the nest. The amount of pheromones spread does not depend on quality or amount of the food, nor the distance travelled by the ant before reaching the source. The effective lifetime of the pheromones in the simulation is, by default, shorter than in reality to enable a more dynamic experience. A motion control was implemented which allows for simple waypoint-based motion and basic obstacle avoidance. To not interfere with the principle of local knowledge, upon collision with an obstacle, the ant rotates to a random direction pointing away from the collision plane and moves a small distance, before again continuing to the currently active waypoint. The distance walked is increased with every collision to increase chances of passing complex

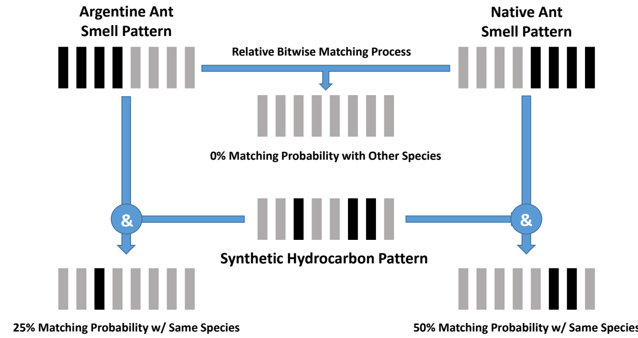

Figure 6: The comparison of binary smell patterns of the ant species may result in friendly behaviour or combat. The user may distort the smells by spraying synthetic hydrocarbons on the ants.

obstacles. It is reset as soon as a waypoint is reached. Unreachable waypoints are skipped when a time limit is met and the next one is approached. The final waypoint is always the nest. This behaviour is simplified, but reasonably within accordance to the actual ants behaviour, specifically in terms of landmark-based navigation and path vector integration. The three states, *Combating*, *Searching* and *Returning* are covered as follows: Ants in combat do not move at all. Ants carrying food will try to retrace the way that brought them to the food source, applying obstacle avoidance as described above. Ants searching for food use their pheromone map for navigation. They sample their position every 0.8 seconds to memorize their path to the nest. When moving within a certain distance of a previously stored location, the points recorded since this first occurrence are forgotten. Every $\frac{1}{7}$ of a second, an ant evaluates the pheromone values approximately ahead of it. The target direction of the ants is then blended linearly between a random walk and rotating as specified by *Turn Angle* towards the direction of the most intense scent, with full pheromone control at *Pheromone Threshold* (Table 1).

4.3 Identification, Combat and Reproduction

In analogy to the findings by Obin [19] and Torres [25], a "smell" was realized in the simulation using 8-bit identifiers that are unique to each of the ant tribes. Every ant provides a smell that can be accessed by other ants, as well as a matching method comparing the native smell to a newly encountered one. Better (bit-wise) matches between the smells of the virtual ants result in greater probability of correctly identifying friendly peers. To implement the synthetic hydrocarbons, a mechanism allows to temporarily superimpose a smell over the native smell. This "synthetic hydrocarbon smell" pattern (Table 1) is bitwise conjugated with the native smell, which also allows simulating different effects on multiple ant species. As shown in Figure 6, Argentine Ants suffer a higher probability of misidentification than native ants, but both are affected negatively. We strongly simplified the combat behaviour between the two ant species, but consider the odds based on the species' attributes. If an ant identifies another one as hostile, they enter a fight. With each attack, attempted every 0.5 seconds, effected damage is subtracted from the opponent's health points. To include some randomness, each ant has a 25% chance to block an opponent's attack. If an ants health points reach 0, it is removed from the simulation. As long as enough food is stored in the nest and the population limit has not been reached, new ants of the species will be spawned at a fixed rate close to the nest, requiring a species-dependent amount of food.

5 Logging and Data Visualization

To allow for meaningful experimentation, a logging mechanism exists that creates machine readable data output in the standard *.csv*

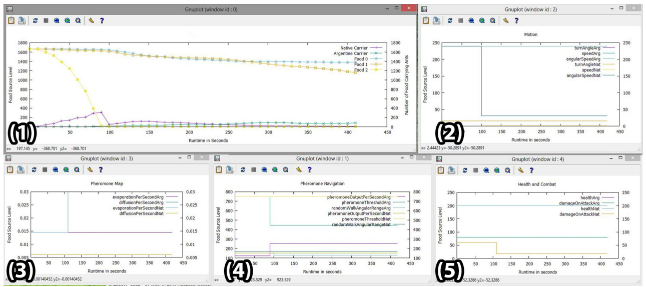

Figure 7: Data visualization using the logging facilities and Gnuplot. (1) Foraging performance: Development of food sources (declining graphs), number of ants carrying food (spikes), (2) motion parameters, (3) pheromone map parameters, (4) pheromone navigation parameters, (5) health and combat parameters

format, compatible with virtually all data processing tools. *Gnuplot* scripts are added to the logging folder, which can be used to visualize the development of the simulation already during runtime, as seen in Figure 7. The data contains information about the ant population, food source levels, the number of ants in specific states and the current parameterizations. Periodically taken screenshots allow to retrace and analyze the development of pheromone paths.

6 Results

Over the course of our work, the focus shifted from a gamified, multi-scale ant species simulation to an interactive simulation sandbox. In general, preliminary feedback we received shows that the simulation is intriguing and accessible. The virtual tools and interactive parameterization option invites the user to experiment and better understand the concept of pheromone navigation. Performance allows to simulate sufficient numbers of ants at good to acceptable frame rates, but could be improved. Logging provides the means to evaluate and compare performance of different model configurations. The different implemented aspects provide a vivid and dynamic framework for observation, learning, and experimentation. Preliminary evaluation of the interactive simulation by eight test users brought very positive feedback with regards to visualization of the virtual world, the ants, view augmentations and usability. The observation of the path formation and inter-species interaction is accessible and entertaining. Integration with Oculus Rift DK2 was considered a highlight, although hardware bottlenecks limit the full experience by enforcing rather low ant population limits.

6.1 Head Mounted Display and Cognitive Experience

When a user launches the simulation for the first time, it is necessary to familiarize him or her with the mapping of the input device[1], before the user puts on the HMD. Once inside the simulation environment, the user finds himself in a life-sized virtual environment, which aids his sense of orientation. Depending on his or her previous experience, the user should get comfortable with the controls within a few minutes of gameplay. Physical movement of the user translates directly into the virtual world, however the narrow frustum and inconsistent performance of the position tracker that was available limited this free motion experience. When observing the behaviour of ants, the freedom in motion allows for an intuitive exploration. To aid with gaze selection, a visual marker for the current location interpreted as the users intended targeting/selection had to be added. To select an action, the user can find virtual tools on a prominently positioned shelf. Here, a trade-off between reducing button mappings and localizing actions within the virtual space was made, as taking objects from the shelf takes more time than simply cycling through a number of always-available tools. Build-up of slight nausea could not be fully eliminated, though sessions of 10 - 15 minutes have been taken without negative physical effects by multiple users. The elimination of many non-user controlled transitions in position and orientation increased the experience significantly. User-triggered, abrupt changes in orientation and position of the view (i.e. aligning the virtual position with the users gaze) showed less severe side-effects.

[1]We used a Microsoft XBOX ONE Wireless Controller with two analog thumbsticks, one d-pad, two analog shoulder paddles and 10 buttons.

6.2 Performance

In our laboratory (Test Hardware: Intel Core i5-2380P Processor, 16 GiB RAM, ASUS GT 430 1GiB DDR3; Software: Windows 8, Unity 5.2.1f), 4K ants could be simulated at 25 fps. Due to the required constant frame rate of above 70 fps for the Oculus Rift DK2, the number of ants for a good VR experience currently remains limited to about 1000 instances. However, the simulation remains playable, but noticeable stutter occurs. According to profiling using the Unity SDK, the frame rate is mostly limited by logic processing and collision detection, not by graphics performance.

6.3 Gamification

Concerning the gamification, the starting point of 750 ants, which is too low to allow effective exploitation of remote sources, and the presence of the Argentine Ant necessitate quick actions in the initial phase of any game round to avoid mixture of the ant tribes and quick eradication of the native species. The water hose proves effective at interrupting pheromone trails, but highly frequented trails will be rebuilt quickly. Furthermore, it can be used in an assisting way by removing trails to depleted sources, encouraging ants to begin searching for new food sources faster. The synthetic pheromone dispenser allows the player to direct the ants effectively, and help them exploit remote food sources they would not necessarily have found. With the hydrocarbon dispenser, a considerable amount of ants can be made to attack their fellows by using it at crowded locations like ant trails, quickly diminishing the size of the tribe.

6.4 Foraging Performance and Navigation

In the default configuration, the expected foraging behaviour of the simulated ants can be observed. Example results have been visualized in Figure 8, where a comparison between default values and the effects of a decreased pheromone evaporation rate can be seen. The agents exploit closer food sources first and generally manage to exploit food sources even when direct paths are obstructed. Sources close to the nest usually get found quickly in the starting phase due to the higher density of ants around the nest. With increasing population size, food source exploitation becomes more consistent even for remote locations, but the presence of obstacles reduces the success rates, as expected. Good results are achieved beginning with 1.25K ants. Trails to depleted food sources tend to become extended to reach new food sources, even in presence of shorter possible paths, if a high percentage of ants was bound by them. Paths tend to change slightly over the time of their usage. A certain bias of the paths to diverge at the food source and form a sharp turn, as well as seemingly random deviations from the path that provoke detours can be observed, which hint at possible implementation artefacts in the motion control. Already depleted paths tend to reappear if a high number of ants memorized them, but will be altered over time. This might also be a result of the maximum pheromone value or a low number of free-roaming ants that can discover new paths. Though foraging performance is similar for both simulated ant species, the presence of the Argentine Ant quickly reduces the number of native ants below the 1K mark, and remote food exploitation deteriorates rapidly. Walls can be succesfully used to block ant trails and force ants to discover new paths. Due to the simplified obstacle avoidance, ants might get stuck if encountering complex

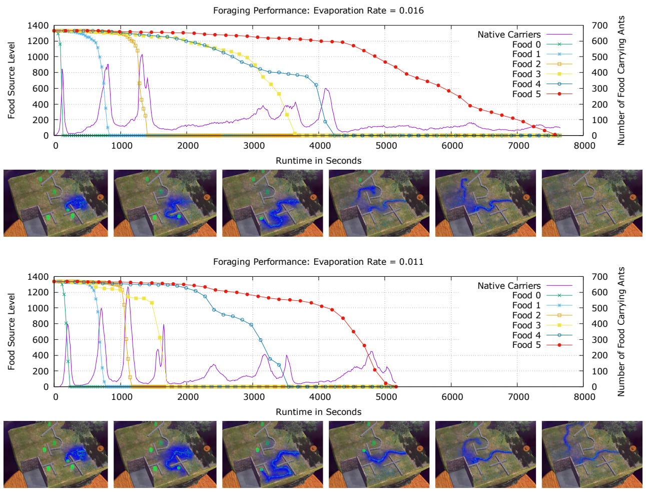

Figure 8: Foraging performance plots with screenshots showing the paths formed. Food levels denote individual food sources. *Native Carriers* counts food carrying ants. Top: Experiment with default parameters. The last food source is not efficiently exploited. Bottom: Identical setup, but decreased *pheromone evaporation* (0.011 versus 0.016), leading to higher performance.

features upon returning to the nest. Also, performance deteriorates on encounter of new obstacles during the return phase. Both situations might ultimately force an ant to ignore all stored waypoints and just be randomly reflected by obstacles until it reaches the nest by accident.

7 Future Work

Considering the latest advances in Virtual and Augmented Reality gear, the integration of a more sophisticated control concept including full spatial tracking of the user and the use of dedicated hand tracking controllers present useful enhancements. From a biological point of view, the ant model should be further extended to include more sophisticated representation of true behaviour, including the use of quality-dependent spreading, a more detailed obstacle navigation mechanism, and a more sophisticated abstraction of the path vector integration, and land-mark navigation. Addition of a serialization of the simulation state and the current parametrization of the tribes would improve the reproducibility and evaluation of scenarios. Improvements in raw performance, either through algorithmic optimisation, (massive) parallelization or hardware upgrades are expected to have a considerable impact on the overall quality of the virtual experience.

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