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THE COLLECTIVE BEHAVIOUR IN STIGMERGIC SWARM

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DECLARATION

This thesis project is presented as part of the requirements for MSc in Artificial Intelligence awarded by the University of Edinburgh. I hereby declare that this project is entirely the result of my hard work, research and enquiries. I'm confident that this work is not copied from any other person. All sources of information have been acknowledged with due respect.

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ABSTRACT

The fields of Swarm Intelligence and Robotics have been fascinated with the organisation and functioning of natural swarms, that has proved its ingenuity and capabilities in sustaining themselves with intelligent behaviour and complex activities emergent from simple attributes or functions of individuals in the swarm. This thesis project delves into the world of insect swarms, with focus mainly on ant colonies or swarms. These ant swarms are referred to as social insects, and cooperative labour define their life. This work considers the foraging behaviours, recruitment communications and pheromones that are observed in ant colonies to understand the processes that entails the foraging task, and hybridizing one or more of these processes to study and verify: (a) The standard and normal way in which we replicate processes in natural systems into models that can closely describe them, in order to implement them physically or gain further understanding of these natural systems and how they work, and (b) the option of also hybridizing one or more of these processes or models to improve the feasibility in implementing these swarm behaviours practically. This hybridization can create redundancies and functions that can account for our imperfect replication and description of the inner-workings of the processes of these natural systems or swarms. This thesis studies the foraging behaviour of ants by specifically looking into fire ants, where pheromones are used to excite the ants into different processes. This can be termed - novel foraging behaviour. The novel foraging behaviour is then hybridized with birds flocking behaviour, which is termed - hybrid foraging behaviour. The novel foraging behaviour and its hybrid version are modelled and simulated, where experimentation and comparison are conducted. The hybrid foraging behaviour predictably showed better performance in the undertaking of the foraging task given several swarm and world instances. In conclusion, this research shows acknowledgement to the adaptation of hybridization of models and processes to allow for improved implementation of processes of natural swarms and systems in their natural ecology into our developing artificial ecology.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

EM	Electro-Magnetic

Chapter

1

INTRODUCTION

This chapter introduces the concepts of swarm intelligence and foraging as seen in ant colonies. The other topics introduced in this chapter are the objectives, the experiments, significance, problem to be treated and motivation.

1. INTRODUCTION

1.1. OVERVIEW

Swarm colonies ranges from social insects to schools of fishes and flocks of birds. They have shown fascinating complexities that arise from intelligent behaviours, which emerges from simple interactions of the individuals, among themselves and with their environment. This phenomenon has drawn attention from researchers in diverse fields of science, biology, computation or informatics and so on, to gain extensive knowledge and understanding of how simple-minded individuals of a swarm can create complexities as a group, that far exceed their individual abilities. This phenomenon is termed swarm intelligence and has been researched and observed for over centuries. The implementation of swarm intelligence in artificial swarm (man-made), like multi-agent robots and simulations, has been researched and worked on since two to three decades ago [1, 2, 3, 4]. This has led to diverse models and methods that describe the processes that entails some of the intelligent behaviours observed in swarms. The models and methods that researchers derive closely describe these natural processes observed in swarms and helps in understanding them. As a result, the implementation of these models and methods as an attempt in replicating these swarm processes and behaviours to reap its benefits has created the field of swarm robotics. Over the past decade, researchers from the field of artificial intelligence and informatics are increasingly drawn and interested in swarm intelligence, as studies [5] have revealed that there exist no centralised coordination mechanisms behind the synchronized operation of social insects, yet their system-level functioning is robust, flexible and scalable. These properties are very much desirable for multi-robot and collective systems, which is a major motivation for swarm robotics.

Swarm Intelligence can be simply defined according to [6] as “the study of how a large number of relatively simple physically embodied agents can be designed in a decentralised way, such that a desired collective behaviour emerges from the local interactions among agents and between the agents and their environment”, where inspiration is garnered from social insects. The decentralised structure and organisation of swarms produce the properties as seen in [6]: (a) Robustness – “the swarm should be able to continue to operate, although at lower performance, despite failures in the individuals or disturbances in the environment” [6]. (b) Flexibility – “the swarm should have the ability to generate modularized solution to different tasks” [6]. (c) Scalability – “the swarm should be able to operate under a wide range of group sizes” [6]. Insect swarms are social insects because almost every task is done in a collective manner, and emergent behaviours are observed as the individuals cooperate by direct or indirect communications.

Roboticists and researchers use various models and methods to describe or implement swarm intelligent processes or tasks for the purpose of replication in multi-agent or collective system and simulations. Some Scientist and researchers have described hypotheses and theories that explain the phenomenon of some swarm intelligent processes or tasks like foraging, aggregation, flocking etc. Thus, producing diverse implementation in simulations with little or no practical implementation in multi-agent or multi-robot systems for real world scenarios. Models, methods or theories that describe some swarm intelligent behaviours are mostly based on: (a) Probabilistic models [7, 8, 9, 10], (b) Bio-inspired models [11, 12, 13, 14], (c) Theoretical or Hypothetical models [15, 16, 17] (d) Hybridized models of similar, or diverse swarm models, algorithms or behaviours [18, 19]. The classification listed above show how researchers attempt to model natural processes or tasks that are observed in swarms and result to complex and intelligent behaviours. The tasks and processes observed in swarms are in-exhaustive as some are not yet discovered or fully understood, especially processes that exist in the biology of the individual ants. Some of these tasks observed and modelled are aggregation, foraging and recruitment communication, pattern formation, object manipulation, cooperative object transportation, scouting, flocking as observed in bird flocks, schooling as observed in fishes, path formation etc.

The past and present standard in bio-inspired research and implementation in fields of informatics and artificial intelligence aims to replicate and describe observed natural phenomenon like swarm intelligence into a model. This thesis work questions this standard on the basis that: for successful implementation of swarm intelligence in artificial agents or robots to perform tasks in real world scenarios, we should adopt the hybridization of models, algorithms or behaviours inspired from similar or different swarms. This thesis makes an opinion that simply capturing the essence of life in nature or processes observed in swarms and replicating it in our artificial systems would need a perfect knowledge of the inner-working of the individual life-forms that make up the swarm and a perfect replication [1, 20]. The characteristics and attributes observed in individualities of a swarm of bees, ants, termites etc. are specially and perfectly inbuilt in them to enable their survival, co-existence and the required performance of assigned roles. The perfect knowledge and replication of natural phenomena is very difficult, if not impossible to attain. Hence, we improve our imperfect replication and description of these processes and phenomena as models for implementation in artificial systems, by augmenting or hybridizing features, rules, designs, algorithms, or models that describe similar or different processes and phenomena. Asking these questions and hypothesizing, this thesis makes the opinion that: to implement bio-inspired models into artificial systems and enable them to work, it is much more favourable to implement a hybrid of bio-inspired models that have a level of similarity, cohesiveness or complementation between them, to increase its feasibility and performance. Applying a hybrid of models that describe natural or swarm intelligent phenomena should provide swarms in artificial systems with attributes, characteristics and functions that are proven over the years by nature to work. These models can act as supplementary or complementary alternatives that would average out the imperfection in each of the models that constitute of the hybrid model, therefore, providing redundancies to improve the operation and design of the base model if present.

1.2. OBJECTIVES OF RESEARCH

The aim of this thesis is to research on the foraging behaviour of ant swarms, which can specifically be fire ants. Insect swarms have been investigated over the years, and various attributes [6, 21], interactions [6, 13, 22] and behaviours [21] are considered to be sources of complexity despite the simplicity of the individuals. The background and review sections in chapter 2 [see section 2.2–2.4] discuss the processes, attributes and behaviours that enable ant swarms to perform foraging tasks. This thesis considers these described processes of foraging, which describes the natural way in which foraging occurs in insect swarms and aims to compare this foraging process with a simple hybridized version of the same foraging process.

In the natural process of foraging, the foraging ants perform a behaviour of trail following or excitation, that occurs as they detect pheromone trails from the nest. This behaviour is also complemented with an orientation behaviour. These behaviours would help guide the foragers to the location of a food source, also by means of tropotaxis [see 2.2.1]. In the hybridized version of foraging, the trail following, and orientation behaviour is hybridized such that each forager would form flocks or clusters on detection of the pheromone trails from the nest. This flock would operate according to the initiator process (Chorus-line hypothesis) described in [16], where the initiator would be the one to command the flock, sometimes temporarily, until a new initiator takes command. According to the study in [16], the flock make good attempt to discern an initiator's movement and reacts to it appropriately. Instead of the foragers to follow the trail as has been done originally (naturally), they cluster together, which can coincidentally form shapes or patterns, and begin to observe the initiators movement. The initiator would use tropotaxis with the aid of induced behaviours from the pheromones to decide its movements and the flock would attempt to discern these movements while staying ignorant to the effects of pheromone trail if in position of detection. Hence, to be the initiator, any of the foraging ants that is currently located in the pheromone trail's active space, with the highest concentration of pheromone detected compared to its flock mates, takes command as the initiator. This situation can change for any current initiator as the flock moves through the trail, therefore giving rise to new initiators. Further details of these processes are covered in chapter 2 and 3.

This thesis therefore questions the implementation of swarm behaviours in artificial swarms by supporting the implementation of hybridized behaviours over the implementation of replicated behaviours. The hybridization of some of these replicated processes and behaviours to be implemented in artificial systems and simulations improves the performance and account for the imperfect replications that might very well be highly susceptible to uncertainties in the environment and present a difficult adaptation to man's (or an artificial) ecology, hence causing inefficiencies and failures.

1.3. SCOPE OF RESEARCH

This research thesis focuses on the foraging behaviour that can be observed in ant swarms like the fire ants, because by researching and studying this behaviour, all the processes employed by the individual ants in the swarm to develop complex macroscopic behaviours are unveiled and has been observed by various investigations and studies [23, 24, 25]. The processes that make up the foraging behaviour and causes it to emerge from the interaction between ants and their environments or themselves are studied, simulated and experimented on to compare novel foraging behaviour and a hybridized foraging behaviour. The foraging behaviour is an important phenomenon defined in natural swarms to enable their survival, therefore the study and implementation of foraging behaviour in artificial system creates a large range of applications in a variety of fields and use cases. This makes it an attractive choice when implementing or researching swarm intelligence, by also allowing researchers to observe emergent collective behaviours. The model that describes the novel and hybrid foraging behaviours are discussed and handled in detail in chapter 3.

The models used in this research and its experiments focuses on a swarm of foragers, where the diverse and in-exhaustive functions of pheromones are not studied, but only its influences in the foraging behaviours are taken into account, and the roles of a queen or king ant in the emergence of foraging behaviour are not studied or experimented on. The parameters that define the world setting, the number of leader (scouts) or follower ants, number of food sources, are all determined based on the research questions [see 2.7] to be answered. In other words, the roles of queen or king ant are also implemented based on the research questions.

This thesis work studies the foraging behaviours in ant swarms in order to provide an insight and answer that can help in the implementation of swarm intelligence or natural phenomena in artificial systems and swarms, by supporting and suggesting the hybridization of models, behaviours or algorithms to be used. This work does not suggest that the processes or behaviours employed by natural swarms and various lifeforms that leads to the emergence of natural phenomena and complex or intelligent behaviours, are not good enough for them. The processes employed in natural swarms and lifeforms are processes that might have evolved from various base processes in order to facilitate their survival. These are processes that have enabled their systems to function as desired, and therefore this work does not make opinions on those processes that have been defined by these swarms and lifeforms, but instead make opinions on the processes that are to be defined in artificial swarms that are meant to survive in man's ecology.

1.4. SIGNIFICANCE OF RESEARCH

This research thesis aims to provide insight that challenges a lot of bio-inspired implementations in artificial systems. Some of the infinite number of natural phenomena happening around us, ranging from reactions and processes in the solar system down to molecular processes taking place at a microscopic level has been studied and researched for centuries. Thus, allowing us to know more about our environments and planet. Further research and investigations revealed intelligent processes that emerge from simple lifeforms and their interactions. These processes have been studied and some modelled, so that an understanding of what is happening is attained. By understanding these processes, the benefits are unveiled, hence attracting the implementation of these processes in artificial systems for variety of use case. This thesis work aims to improve the implementation of these natural processes into artificial systems. The result from this thesis could have an impact on future bio-inspired implementation of natural phenomena, by providing a direction that improves or ascertain the realisation of these phenomena in artificial systems.

1.5. LIMITATION OF RESEARCH

All the circumstances that surrounds the foraging behaviour of an ant swarm are not yet known, cannot be fully understood, and cannot be perfectly replicated in artificial systems or simulations. Basic behaviours and processes that has been observed, are studied and replicated to induce foraging. Many observed complex decisions and behaviours that are induced by pheromones, are not studied in this thesis due to the in-exhaustive nature of these behaviours, and the limited time available to conduct this research. Instead, the core processes that induce foraging behaviour has been studied and implemented for research and experimentation.

Due to the limited time available, hardware implementations of the novel foraging behaviour and the hybrid foraging behaviour are not accomplished. Hence, the results and inferences would be made from what is observed in simulations. The simulation aims to keep the processes as simple as possible, so that the results are more concise and more authentic, because the agents represents simple-minded ants. The natural processes that induce foraging and the process describing the flocking of birds to be used for hybridization, are processes and models described in research works that make good attempts in understanding and describing the inner-working of them. These research works are reviewed and discussed in chapter 2. As a result, the inferences and results derived from this research thesis are authentic, considering that they are gotten from simulations that are based on processes and models that researchers have observed, investigated and verified accordingly.

1.6. ORGANISATION OF RESEARCH

This research thesis is structured into 7 chapters and an appendix, and these are:

- Chapter One – INTRODUCTION.
- Chapter Two – LITERATURE REVIEW: This chapter presents discussion of the background of this study and reviewed works that have influenced the design of the research experiments, simulations and characteristics of the agents. The reviewed literatures describe functions and processes of the ant swarms to be replicated for simulations to undertake the foraging tasks. This chapter also discusses some recent research that show the significance, diversity and applications of swarm intelligence and robotics. The research questions are presented thereafter.
- Chapter Three – METHODOLOGY: This chapter presents the models that are used to construct the simulations and experimentation for the novel foraging behaviour and the hybrid foraging behaviour. The rules, parameters and variables that are used in the design of the experiments are presented and discussed.
- Chapter Four – RESULTS AND ANALYSIS: This chapter presents the results gotten from the experiments conducted in the simulations. These results are presented in graphs. Thereafter, analyses of these results are presented. The analyses of the results would provide answers to the research questions presented in chapter 2 [section 2.7].
- Chapter Five – DISCUSSION: This chapter presents a discussion based on the research conducted and its results.
- Chapter Six – CONCLUSION: This chapter presents a summary derived from this research. Future works that could arise from this research are also discussed.
- Chapter Seven – REFERENCES: This chapter presents a list of research works that has been studied, that helped in influencing this research and was cited.
- APPENDIX: This chapter presents additional information used in conducting this research and experiments.

Chapter 2

LITERATURE REVIEW

This chapter presents discussion on the background of the research, and the reviewed works that influence the design of the research experiments, simulations and characteristics of the agents. The reviewed literatures describe functions and attributes of the ant swarms to be replicated for simulations to undertake the foraging tasks. This chapter also discusses some recent research that show the significance, diversity and applications of swarm intelligence and robotics. The research questions are presented thereafter.

2. LITERATURE REVIEW

2.1. Overview

Foraging tasks that are performed in insect swarms are means by which they retrieve food and resources for the sustainability of the swarm. From a microscopic level, foraging behaviours observed in these insects vary, but the emerged swarm behaviour shows the recruitment of foragers, and a guided exploration of a previously scouted area with food source. From a macroscopic level, we observe complex and intelligent behaviours, special to the varieties of these simple-minded insects, like the ones seen in bees, ants, wasps, termites etc. One common behaviour found in all foraging behaviour of these insect swarms is communication or interaction, in either a direct or indirect way. Majority of the interactions made during foraging or other tasks are indirect. This indirect interaction was defined by Grasse [26] as Stigmergy.

Stigmergy can be defined [27] "as a mechanism for the coordination of actions, in which the trace left by an action on some medium stimulates the performance of subsequent action". Due to these interactions, individuals in the swarm are able to coordinate themselves accordingly and also make decisions. Hence, at a macroscopic level, we observe complex behaviour of self-organisation. Pheromone is a medium that facilitates stigmergy.

Based on the researches and investigations in insect swarms, the implementation of these swarms or their processes in artificial systems have some requirements that must be fulfilled in order for these artificial implementations to successfully show swarm intelligence. In midst of all these requirements as seen in [6, 28], the most significant requirement of a swarm system is its decentralised nature. Due to the increasing complexities of the tasks performed by swarms, swarms are sometimes defined to have behavioural diversity [21], therefore, becoming heterogeneous, as seen in [29]. An example can be seen in the foraging behaviour handled in this thesis, where we have a scout or leader ant, that leaves the nest to look for food, and then recruits and leads the rest of the forager ants to the food source. Behavioural diversity is also a result of the ant's development in terms of its features or characteristics, that would eventually enable it to assume a role. Despite the roles and behavioural diversity that can be observed in swarms, interaction has been discovered to be the pivot cause and catalyst for the macroscopic observation of complex or intelligent swarm behaviour.

This thesis research focuses on the foraging behaviour of ants, and there are several research literatures that touch on this behaviour by providing research findings, hypotheses, models, theories, descriptions and applications of foraging and its base processes. The background of this research is discussed in the next section, and these literatures are reviewed and discussed in the sections ahead. The processes that allows foraging behaviours to emerge are seen in these literatures and are discussed. Base processes can be defined as processes that induce the emergence of a higher level or more complex behaviour or process.

2.2. BACKGROUND OF RESEARCH

Swarm intelligence observed in natural swarms is mostly a result of local interactions between individuals in the swarm and between the individuals and their environment. The local interaction observed in swarms can be grouped into: (a) Direct (explicit) interaction, and (b) Indirect (implicit) interaction [12, 30]. Tasks performed by a swarm are composed of complex behaviours and phenomena that emerges from local interaction. Simple local interactions create behaviours like aggregation, clustering, pattern formation, navigation, recruitment [9, 10, 11, 12, 18, 30, 23] etc. that allows complex and intelligent behaviours to emerge. Hence, enabling the swarm to perform complex tasks or attain complex behaviours like foraging, nest construction, cooperative object manipulation and transportation, nest emigration, cooperated and coordinated defence against colonial rivals or predators etc. Tasks that are complex can simply be defined as tasks that cannot be completed or undertaken by a single individual in a swarm, because the abilities or behaviours required for the task far exceeds the abilities or behaviour of the individuals.

The concept of emergence that can be observed from the local interactions of agents in a swarm to a resultant of complex and intelligent behaviour or phenomena is crucial and extensively dealt with in [31]. Emergence can simply be defined [31] "as a process where phenomena that arise from and depend on some more basic phenomena are yet simultaneously autonomous from that base". A simple example of emergence: cognition, pointed out in [32] while referring to the definition above, regards emergence not to be merely a sum of the basic phenomena, but something above, which arises from it. [32] "All neurons of the brain exhibit simple input-output mappings, but the general scientific view is that together they are responsible for human cognition, including dreams, thoughts, feelings etc. This human cognition is different from the behaviour of the individual neurons". The concept of emergence can then be applied, and as a result we can refer to cognition as an emergent behaviour. A practical example and the main experimental focus of this thesis is the emergent behaviour of foraging in ant colonies or swarm. Everyone in a swarm is composed of simple behaviours or rules that allow them to go about their daily lives, and by the means of local interaction, these simple behaviours enable complex behaviours to emerge. The concept of foraging which is extensively treated in section 2.3 and 2.4, can be observed in almost all swarms present in nature. These intelligent and complex behaviours allow these swarms to survive and are behaviours that enable the swarms to undertake complex tasks. These intelligent behaviours are emergent behaviours and can be called swarm behaviours, where the behaviour of the entire swarm emerges from the behaviour of the members of the swarm. This shows that swarms are highly-decentralized. The section below discusses the complex task and behaviour of foraging of ants, and the simple behaviours and local interaction that enables the emergence and undertaking of foraging.

2.2.1. Foraging

Foraging can be related to a behaviour observed or task that is undertaken in swarms, where locations with resources are scouted for and exploited thereafter by a swarm or group of foragers that also transport these resources back to the nest. Foraging can be seen in swarm of ants, bees, termites, birds, group of animals etc. The ant foraging behaviour emerges from: (a) an intelligent behaviour termed Recruitment communication, which is facilitated by indirect interaction by means of (b) Pheromones (Stigmergy). Foraging in ant swarms are undertaken by foragers and scouts (leaders). These ants are enabled to have attributes and characteristics that allow them to perform their roles.

This thesis hypothesizes that the development of attributes and characteristics in individuals enables role allocation, which inherently leads to task allocation. The study on pheromones in [24] discusses the pheromones of queen bees and that of the queen and king termites. “In the bee colony, the most dramatic effect of the queen pheromone is in its governance of colony productivity. The absence of a queen or queen pheromone in the colony causes many workers to remain idle. This is because the queen pheromone stimulates comb construction, brood rearing, foraging, and food storage” [24]. “The queen pheromone has a primer effect inasmuch as it inhibits development of workers’ ovaries. In absence of the queen and its pheromone, egg production is triggered in up to one quarter of the workers and false queens and other workers in turn produce queen pheromones” [24]. We can infer that the queen pheromone indirectly acts as an inhibitor for the development of attributes and characteristics that would enable new roles such as queens (false queens). The study in [24] also looked at termite pheromones, where development of castes seems to be governed by complex interaction of juvenile hormone, pheromones and environmental conditions such as food availability and time of year. An example [24] also showed that the absence of a king or queen in the colony causes development of replacement reproductive from pseudergate workers, but with the establishment of a reproductive pair, they secrete pheromones that induce pseudergates to eat the excess of reproductive. “Queen pheromone inhibits female pseudergates from becoming reproductively competent while a male-produced pheromone also inhibits male reproductive system. In absence of a queen, a king secretes a pheromone that stimulates the production of females” [24]. “The proportion of soldiers in colony is also regulated by similar interactions” [24]. We can infer that pheromones of the queen and king also affects the development of attributes and characteristics that would lead to performance of a role (queen or king replacement). However, the identity of the pheromones that modulate the proportion of castes in a colony remains unknown [24]. The study in [33], deals with task allocation in ant swarm as they review works that suggests that ant workers might select tasks based on different features, including their age, body size, genetic background, position in the nest, nutrition, in response to signal from other ants or by comparing internal response thresholds to the need to perform a particular task. It is inconclusive on how ants select the tasks to perform. But from studies in bee and termite colonies, we can infer that the queen or king can secrete pheromones that adjusts the composition of the colony by affecting the development of several attributes and characteristics which indirectly affects the roles or castes in the colony. We can hypothesize that this same process is present in ant colony, where ants make task allocation decisions based on their attributes and characteristics. Hence, the team of forager ants would therefore be very much capable of undertaking foraging activities than a normal worker ant, because its development of the attributes and characteristics required for foraging is more proficient than normal ants (normal workers, solder ants etc).

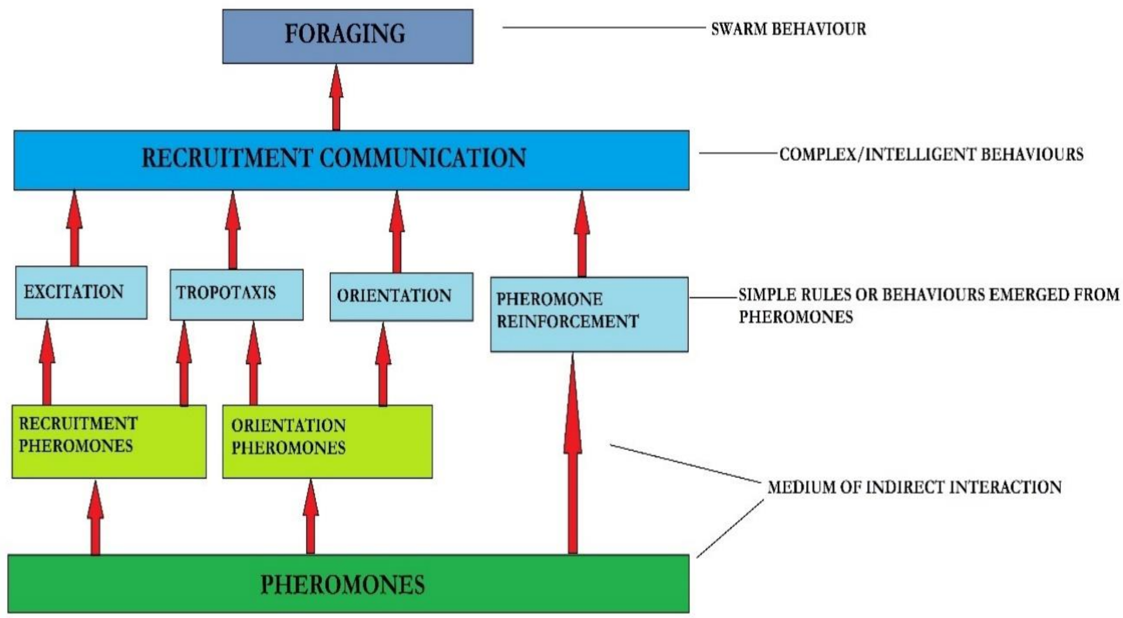


Figure 1. *Emergence tree of foraging in ant swarm (fire ants).*

2.2.1.1. Recruitment Communication

Figure 1 portrays the foraging of ant swarms as a swarm behaviour that emerges from complex and intelligent behaviour termed recruitment communication, which emerges from other processes, simple rules and behaviours (base processes). This complex behaviour has been extensively discussed in [23], where the recruitment behaviours of social insects are handled, and the processes that allows this behaviour to emerge are also discussed. recruitment communication is a behaviour that mobilizes nestmates, which is commonly used by social insects to organize and accomplish tasks [23]. The process of recruitment communication can be simply summarized in ant foraging. When scout ants search for food sources and patrol a colony's territory, scouts that locate the food return to the nest, laying a chemical (pheromone) trial which excites nestmates [23]. Nestmates would then leave the nest and orient along the scout's trail towards the target area [23]. Recruited nestmates in turn, may continue the process by reinforcing the trail.

"Ecology influences the evolution of recruitment communication and the adaptiveness of recruitment behaviour can be studied in reference to patterns in food distributions, predation and competition. Recruitment signals are generally trail pheromones that excite nestmates and orient them to a locus of activity or food source. The physical characteristics of a trail and the response it induces reflect the ecological function of the pheromone" as seen in [23]. This thesis studies the foraging of ant swarm, where the recruitment communication and other base processes are simulated and experimented on in reference to food distribution, composition of leaders and followers in the foraging swarm and the nature of the environment. This is compared to a hybrid version of recruitment communication where a recruitment behaviour is hybridized with flocking behaviour of birds. This foraging and recruitment communication behaviour is discussed in more details in section 2.3, where the figure above is also dissected and discussed. In conclusion Recruitment communication comprises of a host of behaviours that elicit recruitment and therefore facilitates foraging. The process where scouts search for food and locate a food source, and then place pheromone trail as it goes back to the nest, would excite its fellow foraging ants to leave the nest and approach the food location by also reinforcing the trail. Figure 1 show sets of processes and behaviours that facilitates recruitment communication, such as tropotaxis, excitation, orientation and pheromone reinforcement that are induced from pheromones, which can be for either recruitment or orientation purposes.

2.2.1.2. Pheromones

Pheromones has been dealt with extensively in [24], where pheromones are defined as chemical messages that induce a behavioural reaction or developmental process among individuals of same species. The term pheromone is derived from the Greek for "carrier of excitation" and coined in 1959 by the German biochemist Peter Karlson and the Swiss entomologist Martin Lusher during their investigations of chemicals that regulate caste development in termites in 1963 [24]. In 1963, E. O. Wilson and W. H. Bossert of Harvard University formally distinguished two classes of pheromones namely: (a) Releaser pheromones and (b) Primer Pheromones, as seen in [24].

(a) Releaser Pheromones: are messages that induce an immediate behavioural reaction in the receiver. The kind of behavioural responses are diverse, and they include: alarm, defence, aggregation, kin and colony recognition, marking of territories and egg deposition sites, mating behaviours, recruitment, trail following etc. [24].

(b) Primer Pheromones: causes a physiological change in the receiver, like the development of a particular caste or sexual maturation, which eventually modifies the organism's behaviour [24].

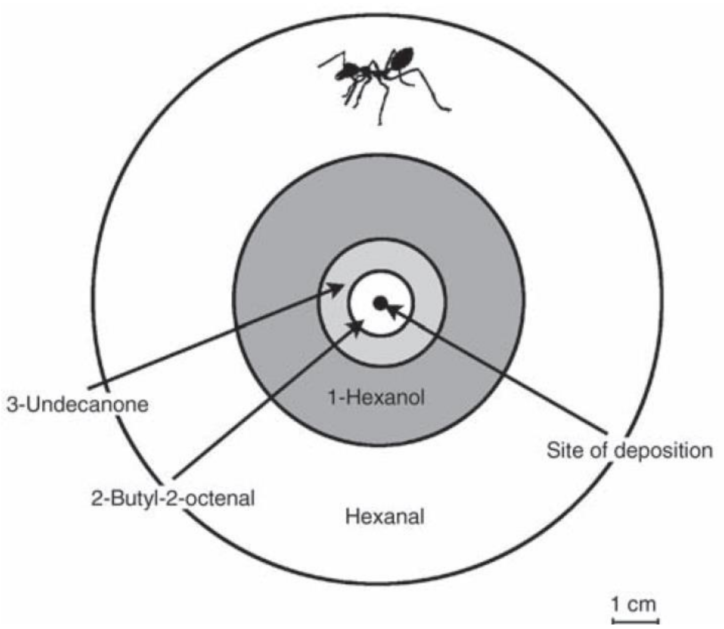


Figure 2. *from* [24] **-** *Pheromone showing the active spaces in still air of the principal components from the mandibular gland of the weaver ant, Oecophylla longinoda. The pheromone has been deposited in the centre of the boundaries of behavioural activity of each component 20 seconds later are represented* [24, 34].

The application and use of pheromones as a medium of indirect interaction is incredibly diverse. This is such that "the communication among social insects, especially among ants, bees, wasps and termites, involves a highly sophisticated pheromonal language in which the interpretation of the individual chemical constituents depends on their particular combinations, ratios, concentrations, and even order of presentation" [24]. "The recent experiences of the receiver and its physiological state is very important in response" [24]. Pheromones are extensively used in almost all ant swarm activities as this enables them to undertake the desired tasks. Some different kind of pheromones that have been observed for diverse tasks are sex-attractant pheromones of Lepidoptera [24], attractant and aggregation pheromones [24], Alarm and defence [24], trail following and recruitment etc.

For foraging, in the case of recruitment communication, pheromones act as a vital process that is required to enable foraging behaviour. Social Insects use pheromone trails of varying permanence to exploit food resources [24]. A foraging worker of the fire ant colony *(Solenopsis invicta*) that encounters a suitable food source, lays down chemical trail by dragging it stinger sporadically along the ground as it returns to the nest [24]. “The pheromone trail is a mixture of farnesenes from their Dufour’s gland. The pheromone trail from one individual does not persist for long, where the active space falls below threshold in less than 2 minutes and its effective length is not more than a meter, hence, requiring reinforcement for continuity of foraging” [24]. “When a droplet of mandibular gland secretion is daubed onto a flat surface in still air, the volatile pheromone diffuses outward at a rate that is dependent on its molecular weight and its diffusion coefficient” [24]. “A region in which the concentration of pheromone is above the minimum required to elicit a particular behavioural reaction is termed an active space” [24]. Figure 2 shows the active spaces of each of the four principal components of the mandibular gland secretion 20 seconds after deposition. In foraging, when pheromone trails are placed, the process described earlier occurs and the foraging ants (followers and leader) make use of tropotaxis.

The spatial processing of the information encoded in an odour (pheromone) trail is by tropotaxis, which is a sampling of the pheromone trail by means of the paired antennae [23]. “Antennal chemoreceptors are used to perceive variation in pheromone concentration along the trail’s semi-ellipsoidal active space, which is an area in which the concentration of the pheromone is enough to elicit trail following behaviour” [24]. By means of tropotaxis, the pheromone gradient, which is formed from the point of deposition outwards as time elapses, is sampled by the antennae of the foragers as the travel along the trail. The regulation of the foraging activity can be done via pheromone reinforcement.

Both processes of recruitment communication and pheromone deposition are vital for foraging and the sections above briefly described their contributions. These complex processes are made up of base processes and behaviours that are studied, simulated and experimented on in this thesis work. The sections ahead extensively discuss the foraging behaviour and its base processes as observed in the reviewed literatures, and the process or behaviour used in the hybridization of the foraging behaviour.

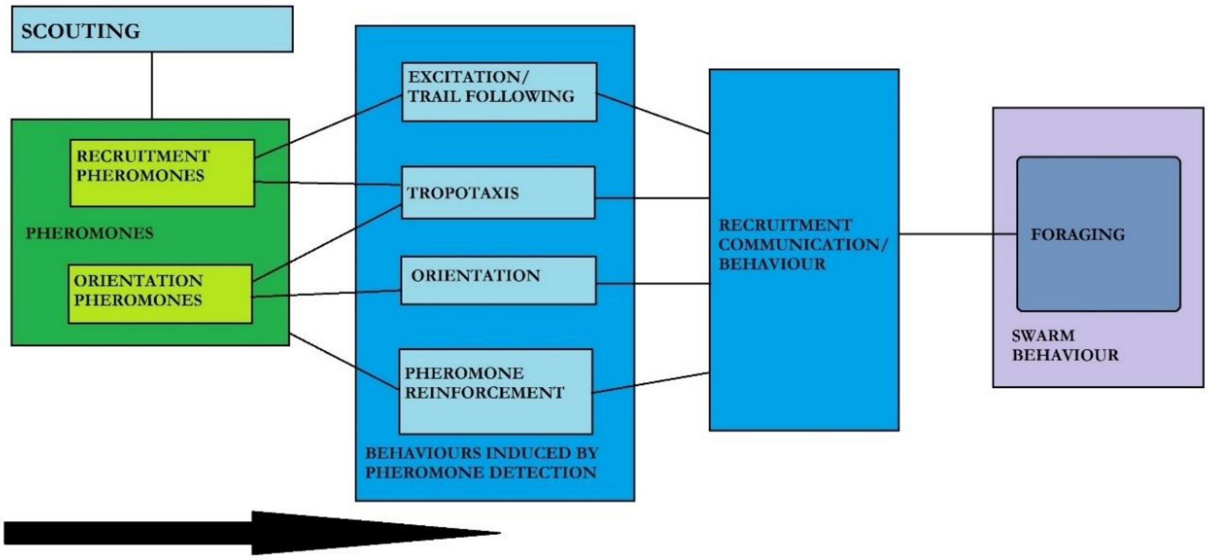


Figure 3. *Diagram showing the connections made by the base processes and behaviours that makes up the foraging behaviour of fire ants.*

2.3. RECRUITMENT COMMUNICATION *by James F. A. Traniello* [23]

In this paper Traniello describes the processes that make up recruitment communication, which facilitates foraging as observed in insect swarms. Recruitment communication is the behaviour that mobilizes nestmates, which is commonly used by social insects to organize and accomplish work [23]. "The mechanism that mediates recruitment communication can be understood by analysing the behaviours of the individuals and signals (pheromones) they produce" [23], as seen in figure 3. Because of the ubiquitous nature of the uses of their pheromones or signals, only uses that concern foraging and recruitment communication will be discussed. In general, social coordination, which enables the swarm to perform many tasks, highly depends on these signals or pheromones (stigmergy). Hence, this literature focused on the recruitment behaviour in social insects, primarily in ants and termites.

The sections ahead discuss the generic foraging behaviour of ants, where base behaviours or processes are also discussed, as described in this reviewed literature.

2.3.1. Description of Foraging Behaviour in Ants

[23] In summary, "workers scout for new food sources and patrol the territory of a colony. When food is located, nestmates are recruited to perform work together. Scouts that have located food return to the nest, laying a chemical (pheromone) trail and sometimes performing behavioural displays to alert nestmates., which then leaves the nest and orient along the scout's trail to the target area. Recruited nestmates, in turn, may continue the process by reinforcing the trail. Regulatory mechanisms involving pheromone evaporation turn off recruitment when the food has been harvested".

[23] In more details, "when workers locate a food, a pheromone trail is created, and on reaching the nest, recruitment pheromones are discharged. Recruitment pheromones are discharged from the exocrine glands, which are anatomical structures often specialized for their synthesis and secretion. The accessory glands to the sting (the Dufour's gland and the poison gland), the pygidial gland and sternal glands, the hindgut, the rectal gland and the tibial and tarsal glands are known to produce substances that serve to recruit nestmates. Other ants can also rely on a variety of glands to produce trail substances (pheromones). These secretions are deposited as a worker travels from a target area to the nest, or vice versa. Trail pheromones can have both recruitment and orientation effects. Although social insects may mix the secretions of different exocrine glands to induce recruitment and trail-following behaviours, or the chemical output of a single gland may be composed of more than one substance, each having distinct role in releasing (inducing) behaviour. Trail communication can therefore be a multisource phenomenon or a process that involves a series of chemical homologs produced in the same exocrine glands. The spatial processing of the information encoded in the

pheromone trail is by tropotaxis, which is a sampling of the trail pheromone by means of the paired antennae".

[23] "Trail pheromones communicate information about food quality to the nestmates that have not had direct experience with a food source. Trail-laying behaviour regulates the pheromone concentration (i.e. the amount of pheromone deposited on a trail), which in turn controls a colony's response. After deposition, a trail pheromone diffuses. The chemical properties of the pheromone both determine the spatial and temporal structure of its active space and regulate foraging activity at the colony level. The concentration of trail pheromone mediates communication between groups of individuals, those that have fed and any potential foragers within the nest. In fire ants, the continuity of the sting (pheromone) trail depends upon the concentration of a sugar solution offered as a food source. The more concentrated and rewarding the solution is, the greater the extent to which the sting is extruded and dragged continuously, and the greater the number of workers that will lay such a trail after they have contacted the food source. The distance between the food source and the nest can also affect the rate at which food is retrieved, and thus the profitability of the colony's foraging".

[23] "The regulatory mechanism underlying the foraging organization is called mass communication. Foraging is initiated when scouts locate new food, determine its quality, and deposit trail pheromone according to the food's energetic value and the colony's nutritional needs. This trail induces recruitment in nest mates, which repeat the cycle of food quality assessment and trail pheromones deposition until the food source has been depleted or the colony satiated. The entire process is regulated by the concentration and evaporation of the trail pheromone. If the recruitment trail is not reinforced, the trail substance evaporates and foraging rate decays over time until food collection ends. Different ant species show variations on the theme of mass communication that likely are associated with the foraging ecology of individual species".

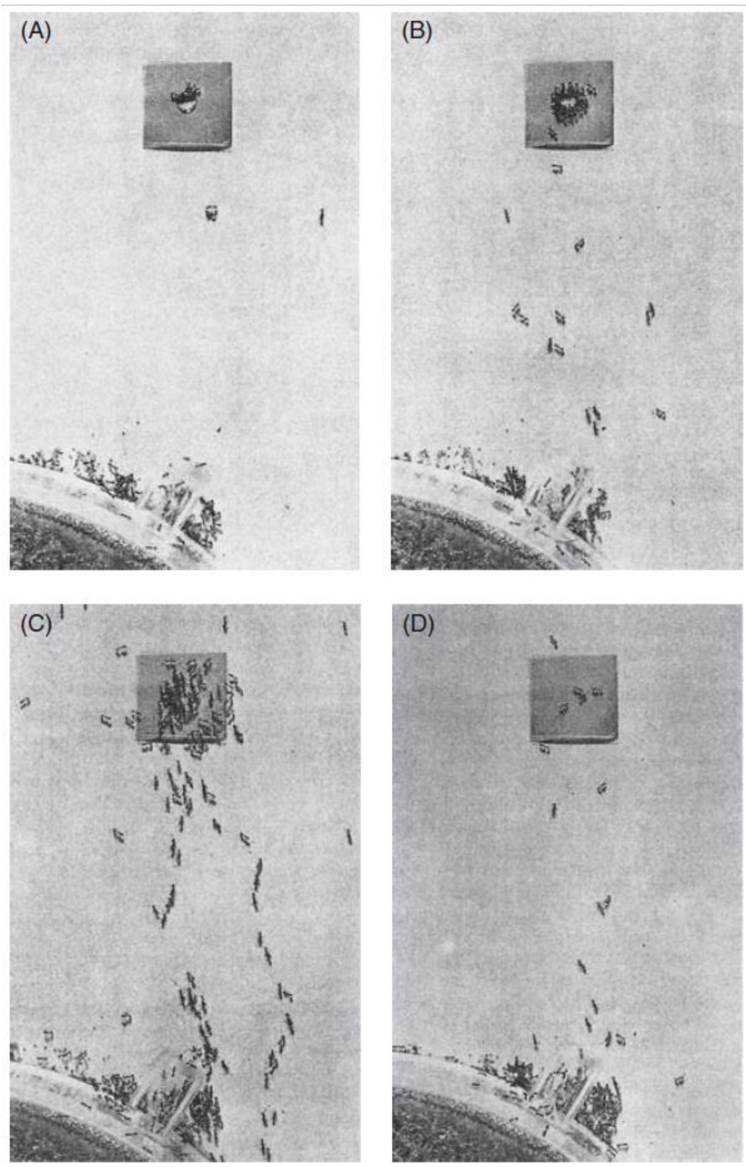


Figure 4. *Recruitment and feeding behaviour in a laboratory colony of fire ants, from* [23]*. (A) Scout ants feeding at a drop of sucrose. (B) Ants initially recruited from the nest by trail-laying workers that had fed now feed and lay trails to the nest. (C) Recruitment increases as more ants arrive at the food and contribute pheromone to the trail. (D) The food is depleted, and new recruits arriving at the food do not lay trails on their return trip to the nest. Foraging now stops because the trail pheromone has evaporated.* [23, 35]

2.3.2. Compositions of Foraging Behaviour

The description of foraging behaviour in ants given in the previous section mentioned the different processes and behaviours that are exhibited in order to facilitate foraging. These processes or behaviours are composed together to define the foraging behaviour of the ants. The sub sections below discuss these processes and behaviours as has been described in this literature. These behaviours are portrayed in figure 1 and 3.

2.3.2.1. Scouting

This is a process in which a worker scout or forage leader, leaves the nest and go to look for new food sources. When a food source is found, the scout marks the food location by creating a pheromone trail from there. This is an initial process, where foraging has not begun, but it sets the stage for foraging to take place. Placing the pheromone trail on its way back to the nest would then recruit nestmates, therefore starting the process of foraging.

2.3.2.2. Pheromones

The pheromones described in this literature are used to create the trails and helps in inducing several behaviours that are covered in section 2.3.2.3. These pheromones are recruitment signals that excites nestmates and orients them to a locus of activity. Two types of pheromones are described, and they are: (a) Recruitment pheromones and (b) Orientation pheromones. Both are discussed below. “The Dufour’s gland of the fire ant is the source of trail pheromone that induces both recruitment and orientation behaviours in workers. Although careful dissection of the kinds and sequences of behaviours in the recruitment process and detailed chemical analyses have revealed that several pheromone constituents may control a number of behaviours associated with recruitment and trail following” [23]. “Dufour’s gland chemistry of fire ants is varied: the constituents of this gland’s secretion regulate different behaviours, which have been called subcategories of trail following. These chemicals include recruitment primers, synergists and orientation inducers” [23].

2.3.2.2.1. Recruitment Pheromones

[23] “Recruitment pheromones induces nestmates to leave the nest to travel to a work site. Trail substances (pheromones), if they have a recruitment effect, will stimulate nestmate to leave the nest or otherwise alter their task performance in the context of a current need”. If a trail is drawn out from the nest entrance and ants leave the nest to follow it, a recruitment effect has been demonstrated.

2.3.2.2.2. Orientation Pheromones

[23] “Orientation Pheromones have no stimulatory effect, but it can serve as a chemical guide for worker traffic. In some ants, nestmates are recruited with a motor display delivered in the nest by a recruiting worker. The trail substance in this case does not have the ability to draw ants out from the nest, rather, it is used as an orientation cue by nestmates that have contacted a recruiting ant”. “If a trail is drawn

out and cannot induce inactive workers to leave the nest, yet the trail is able to orient workers alerted by either a motor display or some other trail chemical that has an alerting property, an orientation effect is occurring" [23].

2.3.2.3. Behaviours Induced by Pheromone Detection (Stigmergy)

Certain behaviours are induced when ants detect pheromone. These behaviours are stigmergic and allows foraging to be performed. The behaviours that are induced by pheromones during foraging as described in this literature are: (a) Excitation or Trail-following, (b) Orientation, (c) Tropotaxis and (d) Pheromone reinforcement. These behaviours are briefly discussed based on this literature in the sections below.

2.3.2.3.1. Excitation or Trail-following

This is a behaviour that is elicited on detection of a recruitment pheromone. This behaviour relates to when an inactive or random ant is compelled to perform an action on detection of pheromones or signals. This behaviour is stigmergic because it was elicited, and not initially decided. The process of recruitment is induced by the pheromone trail deposited by a scout, because the inactive ants in the nest are induced to leave the nest, and hence the behaviour of trail-following is observed. This behaviour is also facilitated by tropotaxis.

2.3.2.3.2. Orientation

This is a behaviour that is induced on detection of an orientation pheromone. This behaviour relates to when ants are compelled to align in a certain degree or direction on detection of pheromones or signals. This is a stigmergic behaviour because it was induced, and not initially decided.

2.3.2.3.3. Tropotaxis

[23] "The spatial processing of the information encoded in an odour (pheromone) trail is by tropotaxis. Antennal chemoreceptors perceive variation in pheromone concentration along the trail's semi-ellipsoidal active space, the area in which the concentration of pheromone is enough to elicit following behaviour". [23]"Theoretically, diffusion yields a gradient of odour (pheromone) molecules; pheromone concentration is highest at the point of application (the centreline of the trail) and symmetrically decreases on either side, defining the boundaries of the active space". [23] "The odour (pheromone) gradient is sampled by the antennae as the insect travels along the trail. When lower concentrations are sensed at the lateral edges of the active space, opposing movements are made so that position within the active space is maintained".

2.3.2.3.4. Pheromone Reinforcement

Once foraging is initiated, pheromone reinforcement or deposition is performed in relation to how much food is left or whether the ant has been fed or food retrieved from food location. This act as a regulatory mechanism and a means of mass communication as previously discussed in section 2.2.1. Until all the food has been harvested or the colony satiated, the pheromone trail would always be reinforced by ants that successfully forage from the food location.

2.3.2.4. Recruitment Communication and Recruitment Behaviour

Recruitment communication and recruitment behaviour are accomplished when the processes and behaviours discussed in previous sections work together. The inter-play of the behaviours and processes seen in sections above creates a recruitment behaviour and communication system, that allows foraging to be possible. This resultant recruitment behaviour is said to have an ancestral source from which it evolved, termed tandem running.

[23] "In this old mode of recruitment, a single nestmate is led "in tandem" from the nest to a new food source: A leader guides a follower to a target area. Tandem running involves motor displays that initiate paring and surface pheromones and their exocrine gland secretions to maintain communicative tie while ants move pairwise, outbound from the nest. This type of recruitment communication and behaviour is considered to be basal because it commonly occurs in ponerine species, which are ancestral in the evolutionary history of ants".

As seen in figure 3, this behaviour and communication systems allows foraging to emerge. From the relationship between these processes and behaviour, a self-organised foraging behaviour is observed, hence, the foraging task is accomplished.

2.4. PHEROMONES *by Ring T. Carde and Jocelyn G. Miller* [24]

In this paper Ring et al, describe pheromones and its different types and functions as observed in various insects. A discussion on the foraging behaviour of ants and the functions of pheromones in foraging is also presented. The pheromones of insects and their functions are ubiquitous, but Ring et al make a very good description of some pheromones and their functions. This section would focus on the foraging behaviour, the behaviours and processes that are composed to facilitate foraging as described in this literature.

[24] “Pheromones are chemical messages that induce a behavioural reaction or developmental process among individuals of the same species. Two classes of pheromones are formally distinguished, which are: (a) Releaser pheromones – are messages that induce an immediate behavioural reaction in the receiver, and (b) Primer pheromones – cause a physiological change in the receiver, such as development of a particular caste or sexual maturation, which eventually modifies the organism’s behaviour”.

Focus would be placed on releaser pheromones, which are employed in foraging. The primer pheromones serve for complex functions that are performed by queen or king ants of a colony. Since focus is on foraging behaviour, this section discusses only the foraging behaviour described in this literature and its relationship with the releaser pheromones. The sub-sections presented ahead describe the foraging behaviour and the base processes and behaviours that facilitates it.

2.4.1. Description of Foraging Behaviour in ants (Social Insects)

[24] “Social Insects use trails of varying permanence to exploit food resources. A description of how foraging system works in fire ants is given: A foraging worker that has encountered a suitable food source lays down a chemical trail by dragging its stinger sporadically along the ground as it returns to the nest. This trail induces recruitment and therefore, foraging begins. The trail pheromone is a mixture of farnesenes from their Dufour’s gland. The trail from one individual does not persist for long – the active space falls below threshold in less than two minutes. They can even adjust the amount of pheromone deposited on the trail by altering how firmly it drags its sting. The amount of pheromone on the trail is regulated by three factors: (a) the number of ants returning, (b) the proportion of ants laying a trail, and (c) the amount that each ant contributes to the trail. When the food is finished, or an ant cannot reach the food source because of other ants, any ant that cannot feed simply does not reinforce the trail”.

[24] “The number of ants recruited to leave the nest for foraging is a direct function of the quantity of trail pheromone released by a returning forager. To induce nestmates to leave the nest and forage along the trail, the returning forager releases much more pheromone than is found along the trail itself. These simple rules followed by individuals allow mass recruitment, a sophisticated system whereby one group of ant transfers information about the quality of a food source some distance away to another group of ants. The seeming disadvantage of the impermanence of such trails is actually a useful feature of the system that permits ants to match the number of foragers to the quantity of the resource”.

2.4.2. Compositions of Foraging Behaviour

The description of foraging behaviour in ants given in the previous section mentioned the different processes and behaviours that are exhibited in order to facilitate foraging. These processes or behaviours are composed together to define the foraging behaviour of the ants. The sub-sections below discuss the processes and behaviours as has been described in this literature. These behaviours are portrayed in figure 1 and 3.

2.4.2.1. Scouting

Foraging workers that have their role as scouts, leave the nest and start to search for new food source. When a food source is located, a pheromone trail is created while going back to the nest from the food location. On reaching the nest, an induced behaviour of recruitment occurs in the nestmates, hence, starting the process of foraging.

2.4.2.2. Pheromones

The pheromones described in this paper are of two types, which are: releaser and primer pheromones. Releaser pheromones are extensively used in the foraging task of ants. The foraging description seen above describes the foraging behaviour of fire ants. The releaser pheromones used by fire ants are known to have both recruitment and orientation effects. Pheromones used in foraging helps to induce certain behaviours that are discussed in section 2.3.2.3.

2.4.2.3. Behaviour Induced by Pheromone Detection (Stigmergy)

Certain behaviours are induced when ants detect pheromone. These behaviours are stigmergic and allows foraging to be performed. The behaviours that are induced by pheromones during foraging as described in this literature are: (a) Excitation or Trail-following, (b) Tropotaxis and (c) Pheromone reinforcement. These behaviours are briefly discussed based on this literature in the sections ahead.

2.4.2.3.1. Excitation or Trail-following

When the pheromone trail is created, if an inactive nestmate detects it, recruitment is induced. This behaviour is seen as a direct function of the quantity of trail pheromone deposited. The process of recruitment relates to the ants being compelled to leave the nest, and then a behaviour of trail-following is induced also. The trail-following behaviour is also facilitated by tropotaxis. This behaviour is stigmergic because it is induced and not initially decided upon.

2.4.2.3.2. Tropotaxis

Tropotaxis is performed by ants to investigate the active space of the pheromone trail and its concentration or messages. A region in which the concentration of pheromone is above the minimum required to elicit a particular behavioural reaction is termed an active space. The active spaces of a mandibular gland secretion twenty seconds after deposition is shown in figure 2.

An example is given of weaver ant pheromones and the decoding of the components in the pheromone trail. [24] At the outer limit of the active space, worker ants encounter only components above threshold levels and perform certain behaviours. Ants that enter the active space, however, move up the odour (pheromone) gradient towards the odour source by means of tropotaxis and performs the desired behaviours.

2.4.2.3.3. Pheromone Reinforcement

When a returning forager has been fed or has retrieved food from the food source, it releases much more pheromones than is found along the trail, therefore inducing nestmates to leave the nest to forage from food location. A returning forager that has not been fed or has not retrieved any food, will not reinforce the pheromone trail, therefore allowing the pheromone to act as a regulatory mechanism and a source of mass communication.

2.4.2.4. Recruitment Behaviour

The recruitment behaviour observed would be an interaction of the behaviours and processes described in the previous sections. As recruitment begins, after the scouting operation, it continues until the food source has been exhausted or the colony satiated. This behaviour is directly affected by the remaining amount of food that can be foraged and the satisfaction of the colony. Once recruitment starts, foraging begins, and once recruitment stops, foraging ends.

2.5. THE CHORUS-LINE HYPOTHESIS OF MANOEUVRE COORDINATION IN AVIAN FLOCKS *by Wayne K. Potts* [16]

In this study, Wayne discussed the chorus-line hypothesis that describes the behaviour of manoeuvre coordination in avian flocks. This description is used to model the flocking (clustering) behaviour that hybridizes the trail-following behaviours of ants. This study looked at how thousands of birds flying together at high speeds are able to execute abrupt manoeuvres with such precise coordination.

Based on the description given by Wayne, the section below presents the behaviour of avian flocks in manoeuvre coordination.

2.5.1. The Behaviour of Avian Flock in Manoeuvre Coordination

[16] "The chorus-line hypothesis suggest that manoeuvres are initiated by any bird executing a manoeuvre towards the flock and that subsequent coordination is achieved through visual communication. This leads to the prediction that execution of manoeuvre by neighbours of the initiator will be delayed by at least their own reaction time but, further away, response time should fall as birds are able to estimate the arrival of the approaching manoeuvre wave".

[16] "Birds are considered initiators when they begin the manoeuvre before the rest of the flock. Manoeuvre are always propagated through the flock in a wave radiating from the initiation site. These waves are observed to travel along every major axis (including back to front), indicating that manoeuvres may be initiated from any region of the flock".

[16] "Manoeuvres initially propagate more slowly than the birds' reaction time and then accelerate to high propagation speeds, as predicted by the chorus-line hypothesis. Flock members always appear to follow the lead of the initiator banking towards the flock. This dictatorial rule by initiators presumably prevents indecision and allows flock to respond rapidly during attacks by birds of prey, which are a major source of mortality for flocking shorebirds".

2.6. GENERAL REVIEWS

In this section, other literatures that have done work in swarm intelligence are reviewed to also show the diversity of swarm intelligence. The literatures show replication of swarm intelligence in artificial systems or robots, where the applications are also mentioned.

In [11], a swarm robot project was conducted, where emphasis on decentralised control, limited communication abilities, use of local information, emergence of global behaviour and robustness was made in the design of the robots. The robots (called s-bots) are able to attach to each other and objects, where activities like collective and cooperative object transportation, aggregation, searching, coordinated motion, exploration, Adaptive task allocation, Navigation on rough terrain, functional Self-assembly were performed in simulation and physically.

(a) (b)

Figure 5. *Graphic visualisation of the rigid gripper used to connect in a secure way among themselves. (a) retrieving/transporting heavy objects, (b) passing over holes.* [11]

In [10], heterogeneous robot swarm of two types are employed to implement stigmergic navigation, where one group of robots called Eye-bots act as stigmergic objects or pheromones that are used to guide the other group of robots called foot-bots, to the desired goal. The Eye-bots are deployed in the ceiling of the test room, and the foot bot are deployed on the ground. The Eye-bots were deployed beforehand to cover the area between start and goal in fixed positions on the ceiling. From these positions they give directional instructions to the foot-bots to guide them towards the start or goal positions. This was inspired by pheromone based stigmergy foraging in ant colonies.

In [18], there is a combination of stigmergic and flocking behaviours to coordinate swarm of drones for performing target search. The drones are deployed, and potential target location are marked with virtual pheromone in the map inferred by all the drones. This approach uses stigmergy to attract drones in areas with potential targets and employs flocking to organize drones into swarms. Simulated results on synthetic and practical scenarios proved the benefits of stigmergy and flocking.

The thesis work done by Russell Edelen in [30], described the robotic implementation of foraging behaviour, with detailed description of various models used for foraging in swarm robotics.

Russell reviewed foraging models in [21] page 78, which are divided into three main classes: Differential Equations, Probabilistic, and Cellular Automation models.

- Differential Equations: [21] these are the most common type of model. This model assumes that individual agents are infinitely divisible individuals behaving deterministically, which is valid with large populations [21]. However, it can be very difficult, due to continuity assumptions and other factors, to formulate a set of differential equations describing the behaviour of certain biological systems [21].
- Probabilistic Models: These models tend to use a discrete approach that models the behaviour of each individual in the group [21]. Simple behavioural rules based on probability are used to generate a few governing equations. Monte-Carlo simulations are often conducted to produce similar results as those obtained from an actual experiment [21].
- Cellular Automation Models: probably the first modelling technique used to investigate swarm intelligence (self-organisation) [21]. This type of modelling simulates groups of biological components by arranging components as points in a lattice or grid and allowing the components to interact according to simple rules.

In Russell's [21] experiment, he made use of seven robots, and introduced sixteen targets at a single location inside the foraging field. The robots are to discover the targets and a trail is laid back to home with an evaporative ink. These targets are collected and dispatched at home location. These pheromone trail introduced positive and negative reinforcement. The experiment was conducted using from two to seven robots in total and this showed a steady decrease in collection time as the number of robots is increased

As number of robots is increased, collisions occur more frequently, therefore cooperation slows down as collision increases [28]. Some reviews, as also seen in [28] page 28:

- The experiment shows benefit of swarm cooperation, but the results were marginal due to the low agent or robot count. In nature swarm intelligence depends heavily on agent numbers and it is not possible to fully demonstrate the potential with seven agents.
- The pheromone method used, and sensor limitations of the robots showed a significant variation between trails. Hence trails were not followed with high accuracy.
- The results attained in this work was compared and used to confirm some hypothetical predictions (concerning Emergent pattern formation, Multi-stability, and the Bifurcation phenomena) of swarms, where most of the hypothesis were confirmed using simulations and very few of them confirmed using hardware implementation.

In [9], an implementation of virtual pheromones in BDI robots (Belief-Desire-Intention) using MQTT (Message Queue Telemetry Transport) and Jason is presented. [9] virtual pheromones are described, which are implemented in Jason, which is a java-based interpreter. While using MQTT, which allowed the implementation of their stigmergic algorithms in a high-level declarative language. [9] describing that Integrating MQTT in their implementation opens up a plethora of solutions in the cloud robotics field. In conclusion, as presented in [9], the presence of stigmergic coordination system among robots allows the decentralisation of the computation outside the swarm, with simpler entities with less requirements in terms of computational resources creating an emerging intelligence from the environment itself.

The paper [9], looks at the large-scale implementation of stigmergy in robot, which would develop a swarm attribute of self-coordination to them. Evidently there is also an interaction with the field of Internet of Things. Figure 6 shows the simple localisation operation of two robots accessing the server to get information on their positions and pheromones.

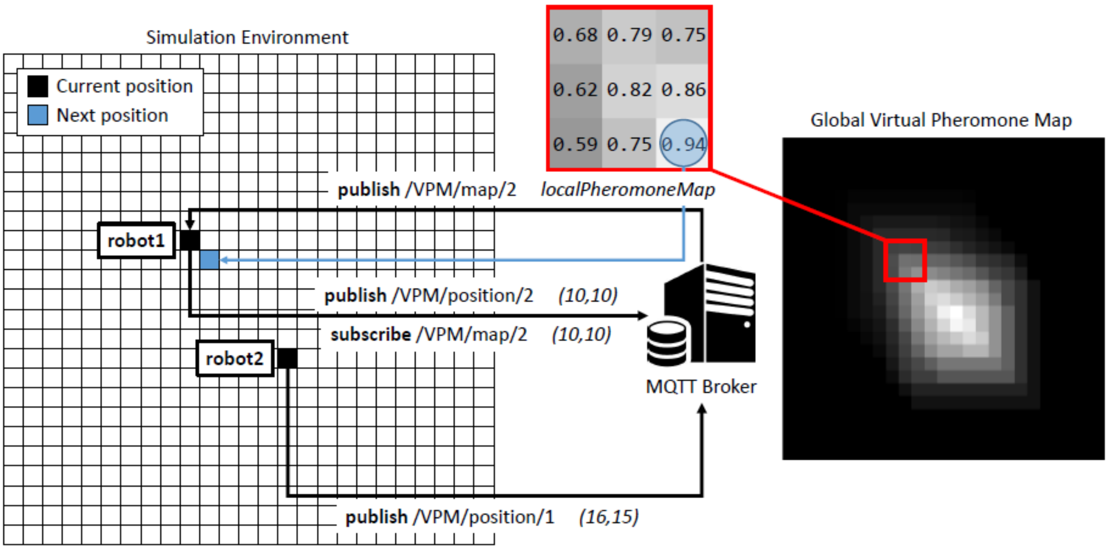


Figure 6. *An example of how two BDI robots interact with the MQTT broker in order to send their positions to the back-end server and retrieve the local pheromone map around their position. [9]*

2.7. RESEARCH QUESTIONS

The questions presented in this section considers the novel foraging behaviour that has been extensively discussed in the previous sections and the hybrid foraging behaviour that hybridized the novel behaviour with the chorus-line hypothesis [see chapter 3]. Given these two behaviours, these questions are asked and are experimented on, to ascertain and infer on which behaviour and method is ideal or preferable for implementation in artificial systems or swarm, in order to realise a system that functions properly in real world scenarios despite uncertainties, and imperfect replications or models used in the implementation.

Research Question 1:

Given a single food location, a single scout (leader), and a finite timespan, how much food is going to be foraged by the swarm when novel foraging behaviour or hybrid foraging behaviour is used, and how is this related to the size of the follower ants?

Hypothesis: Regardless of the number of follower ants, when the hybrid foraging behaviour is employed, the number of foods foraged would be larger than that of the novel foraging behaviour in the given timespan.

Research Question 2:

Given a single food location, multiple scouts, and a finite timespan, how much food is going to be foraged by the swarm when novel foraging behaviour or hybrid foraging behaviour is used, and how is this related to the size of the follower ants and leader ants?

Hypothesis: As the number of scouts (leader ants) increase, the food source is located faster, resulting to faster foraging. Regardless of the number of scouts, the amount of food foraged by using either of both foraging behaviours would depend on the number of followers. The result is same as the first hypothesis, the number of foods foraged using the hybrid foraging behaviour would be more than that of the novel foraging behaviour in the given timespan.

Research Question 3:

Given multiple food locations, a single scout, and a finite timespan, how much food is going to be foraged by the swarm when novel foraging behaviour or hybrid foraging behaviour is used, and how is this related to the size of the follower ants?

Hypothesis: since the swarm has a single scout, a single food source would be located, and the swarm would forage from the food source. Foraging with the hybrid behaviour would have more food foraged than the novel foraging behaviour in the given timespan.

Research Question 4:

Given multiple food locations, multiple scouts, and a finite timespan, how much food is going to be foraged by the swarm when novel foraging or hybrid foraging behaviour is used, and how is this related to the size of the follower and leader ants?

Hypothesis: foraging with the hybrid behaviour would have more food foraged than the novel foraging behaviour in the given timespan. As the number of scouts (leader ants) increase, the food source is located faster, resulting to faster foraging. Regardless of the number of scouts, the amount of food foraged by using either of the foraging behaviours would depend on the number of followers.

Research Question 5:

Given a world with obstacles, with multiple or single food location, multiple or single scouts, and a finite timespan, how much food is going to be foraged by the swarm when the novel foraging behaviour or the hybrid foraging behaviour is used, and how is this related to the size of the follower and leader ants?

Hypothesis: regardless of obstacles in the environment, when scouts locate food sources, they create a safe path back to the nest with the best of their abilities. Hence a path that avoids all obstacles should be created. When multiple scouts are used, the food sources are located faster than the case of a single scout. Regardless of the world settings and swarm settings, foraging with the hybrid behaviour would have more food foraged than the novel foraging behaviour in the given timespan.

Research Question 6:

Given a timespan, multiple or single food sources, and multiple or single scouts, how much resources are going to be used in the foraging task when either the novel foraging behaviour or hybrid foraging behaviour is used?

Hypothesis: The novel foraging behaviour would make more use of resources than the hybrid behaviour. This is because each ant would have to follow the trail independently, and therefore reinforce the trail every time it decays until food has been exhausted. As for the hybrid behaviour, the cluster would use the trail as a group, and hence the reinforcement would only be done mostly by the initiator at every current time when a pheromone has decayed. The hybrid foraging behaviour allows the pheromone trail to be used less but optimally and reinforced less than the novel foraging behaviour.

Research Question 7:

Given either multiple or single scout, multiple or single food source, how much time is used to forage from all food sources if possible when either the novel foraging behaviour or the hybrid foraging behaviour is used?

Hypothesis: regardless of the different world or swarm instances, the hybrid foraging behaviour should take less time to forage all food sources.

Other objectives that can be attained would be to compare the two foraging behaviours based on the following:

- The positive or negative emergent behaviour that is observed as a result of the foraging behaviour
- Practical feasibility of the foraging behaviour if given a foraging related task in real world scenarios.

This research thesis would therefore provide evidence that implementation and deployment of natural phenomena (swarm intelligence) in artificial systems for successful applications would fare better in using hybridized models, methods, algorithms or rules than using models, algorithms, methods or rules that cannot perfectly describe or replicate these natural phenomena (swarm intelligence).

Chapter

3

METHODOLOGY

This chapter presents the models that are used to construct the simulations and experimentation for the novel foraging behaviour and the hybrid foraging behaviour. The algorithms, rules, parameters and variables that are used in the design of the experiments are presented and discussed.

3. METHODOLOGY

3.1. OVERVIEW

The implementation of natural phenomena, processes and models that describe them into artificial systems has been adopted over the years to implement systems that function and is as beneficial as can be seen when natural systems exploit these phenomena and processes. This thesis studies the foraging behaviour of ant swarms, where their applications and benefits are extremely useful in real world scenarios and in solving problems. Due to the imperfect modelling and replication of these natural phenomena and processes, this thesis suggests that these imperfectly modelled phenomena should be hybridized to improve their implementation in artificial systems. This chapter therefore, discusses the novel foraging behaviour and a hybrid foraging behaviour. The novel foraging behaviour of natural ant swarms has been discussed in chapter 2, where its base processes and behaviours are also described. The hybrid foraging behaviour is a bit similar to the novel behaviour, where the difference is in the hybridization of the recruitment behaviour (recruitment communication) and trail following behaviour with the flocking behaviour of birds [see section 2.5]. These foraging behaviours are modelled and closely replicated in simulation for this research thesis.

Both foraging behaviours and their compositions (base processes and behaviours) are described in section 3.2. The models and algorithms that replicate the novel and hybrid foraging behaviour are discussed [see section 3.3]. All the Experiments are done in simulation and are described in section 3.4. The next section introduces the research and describes the novel and hybrid foraging behaviours that are simulated.

3.2. RESEARCH PLAN

The novel and hybrid foraging behaviours are modelled and implemented in simulation. As described in 1.4, the simulations are limited such that the research questions perform the roles of - queen of the ant swarm and creator of the world, by deciding the composition of the foraging swarm and its size, and the state of the environment (world). Therefore, the simulation experiments are run by taking into account the size and composition of the swarm, the state of the world, and the number of food sources as parameters which are used in answering the research questions. For each research question and defined parameters, the simulation experiment is conducted for both the novel and the hybrid foraging behaviour. After all the simulations are done, statistical analyses of the results are conducted, and inferences are made. The sections below describe the simulations and the behaviours to be seen in these experiments.

3.2.1. Aim of Research

The aim of this research is to discover if the artificial or robotic implementation of natural phenomena and processes that cannot be perfectly replicated or modelled due to lack of knowledge or insufficient technology, can be improved upon by hybridizing these imperfect models and replications, so that they act as supplementary or complimentary to each other. This averages out their imperfections to create a system with redundancy that can function better in an artificial ecology. This research is conducted by replicating, simulating and experimenting with the foraging behaviour of fire ants and hybridizing a part of this foraging behaviour with a simple flocking behaviour seen in birds for a separate simulation experiment. These foraging behaviours, the novel and hybrid, are experimented on to answer the research questions presented in 2.7. From the results, this thesis research draws conclusion to discover which method of implementation is preferable and should be exploited.

The methods of implementation that are compared can be classified into: (a) Implementing models that attempt to replicate and describe natural phenomena or processes, and (b) Implementing a hybrid of the models that attempt to replicate and describe natural phenomena or processes.

3.2.2. Simulation

The simulation experiments are conducted in a java-based simulation environment developed by Lenka Pitonakova, termed Creeper [36]. The simulator is suitable for multi-agent and swarm intelligence/robotics simulations. The simulation environment used in this thesis is a virtual 2D world of 800x800 pixels. The simulator is designed to be programmed, so that it provides variables and parameters that can be set to present different simulation scenarios for diverse experiments. The parameters programmed for this research are: (a) World, (b) Leader robots/agents, (c) Follower robots, (d) Number of runs, and (e) Trial Duration. These parameters are used based on the research question that is to be experimented on. They are programmed to initialize an environment where the experiment will be conducted in. More details are provided in section 3.3.

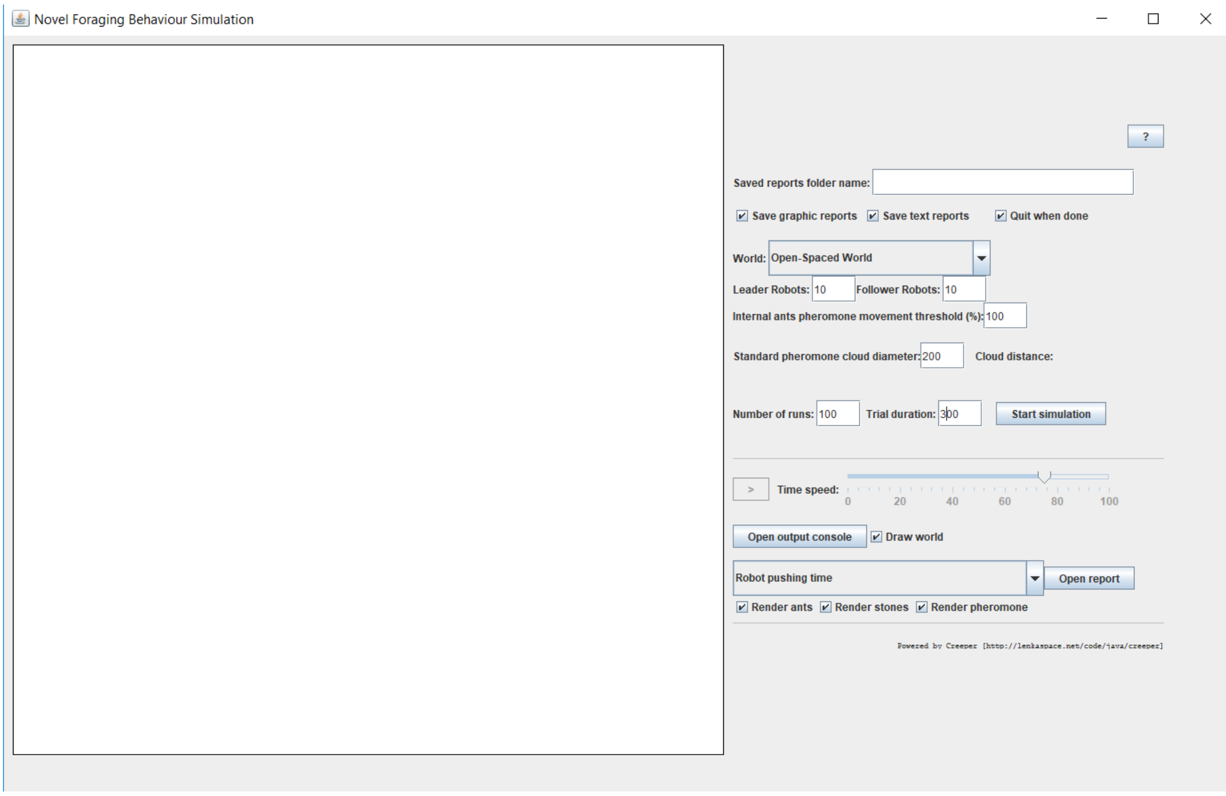


Figure 7. *Creeper Simulator.*

- World: - This parameter sets the world where the foraging takes place. There are four world instances used for the experiments. These are:

- OPEN-SPACED WORLD: - This provides an environment that contains only a nest and a single food source.
- MULTIPLE FOOD-FILLED WORLD: - This provides an environment that contains the nest and two food sources.
- WORLD FILLED WITH OBSTACLES: - This provides an environment that contains a nest, a single food source and multiple obstacles (four).
- MULTIPLE FOOD WITH OBSTACLES IN WORLD: - This provides an environment that contains a nest, two food sources and multiple obstacles (four).

- Leader Robots: - This parameter sets the number of scouts that are present in the swarm. The scouts have the role of finding the food source, hence, the increase and decrease of this parameter, increases or decreases the chances of finding the food sources.

- Follower Robots: - This parameter sets the number of followers (foragers) that are present in the swarm. Since the nest is a fixed size, the changes in this parameter can result to extreme situations of too much or too little swarm members. These effects are taken into consideration in the experiments.

- Number of runs: - This sets the number of times the simulation experiment is run. In this thesis research, this parameter is set to 100 runs per experiment.

- Trial Duration: - This parameter sets the duration in which a run would last for. In this thesis research, these experiments are set to last for 300 seconds per run (5 minutes)

The parameters - world, leader robots and follower robots are used to classify the experiments, and these are presented in section 3.4. The sub-sections ahead give descriptions of the foraging behaviours that are simulated and experimented with. Their base processes and behaviour are also discussed as has been done in previous foraging behaviour descriptions [see chapter 2, section 2.3 and 2.4].

3.2.2.1. Description of the Simulation of Novel Foraging Behaviour

This foraging behaviour is modelled such that the foraging behaviour observed in ant swarms is somewhat perfectly replicated. Some processes and behaviour might differ from the natural ones because of imperfect replication and lack of full knowledge of the biology and processes that surrounds the foraging behaviours of ants. The description given in this section closely describes and shows the foraging behaviour of the fire ant swarms according to the capabilities of the simulator.

In summary, for the novel foraging behaviour, the scout and follower agents are initialised at random locations in the nest. The scouts leave the nest and starts to search for a food source, while the followers move randomly within the nest. When a scout finds a food source, it marks the location, and creates a pheromone trail as it goes back to the nest. When the pheromone trail has been created, the scout then starts to forage. When the followers in the nest detect this pheromone trail, recruitment occurs, and foraging begins. The pheromone trail is reinforced when food is retrieved. When food is exhausted or when food is not retrieved, the pheromone trail is not reinforced, and it decays linearly until its gone, therefore, stopping the foraging process.

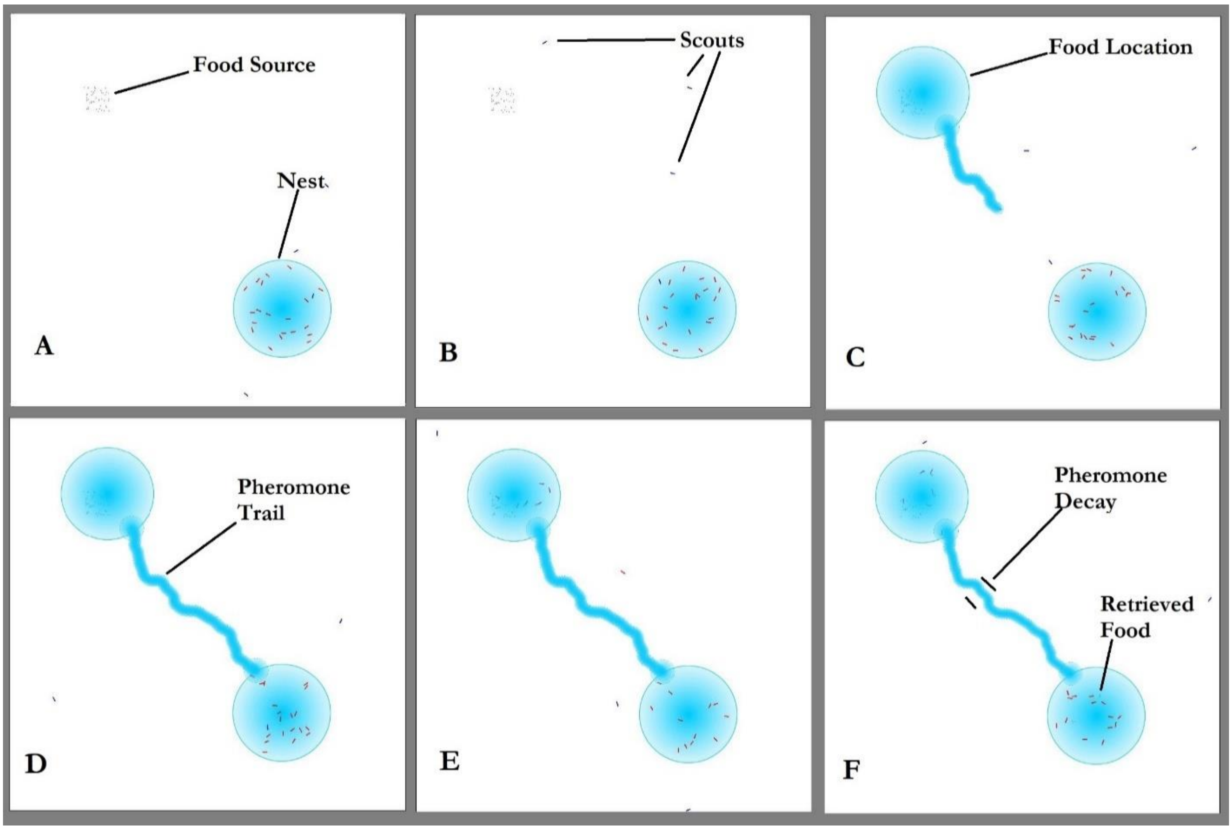


Figure 8. *Novel foraging behaviour simulation in a world with a single food source and a nest. (A) the agents (scouts and followers) are initialised at the nest, (B) The scouts leave the nest to search for a food source, while the followers in the nest move randomly. (C) A food source is located, and its location is marked. A pheromone trail is created as the scout go back to the nest. (D) The pheromone trail connects the nest and the food location, hence, allowing foraging to begin. (E) The scout and followers go to the food location to retrieve food (forage). (F) The pheromone trail decays as time passes in a linear fashion. The pheromone trail is reinforced by an agent that has retrieved food, and foraging continues, else when the pheromone trail decays and reaches a threshold size or potency, reinforcement stops, and foraging stops thereafter.*

3.2.2.1.1. Description of the Novel Foraging Behaviour

In more detail, the scout and follower agents are initiated at random locations in the nest. The scouts leave the nest and start to search for a food source. When a food source is found, it places a highly-potent pheromone that marks out the area where the food source is located. From the edge of the highly-potent pheromone, a releaser pheromone of size larger than the pheromones that will make up the pheromone trail, is placed, and then it creates a pheromone trail as it goes back to the nest. If there are obstacles in its path, the scout avoids these obstacles while heading to the nest, therefore creating a pheromone trail that avoid the obstacles. This pheromone trail can be seen as a safe path created by the scouts according to the best of their abilities. On reaching the nest, it stops creating the trail just at the edge of the nest area, which is marked out by a highly-potent pheromone, which can be that of the queen. At the edge of the nest and the end of the pheromone trail, a recruiting pheromone (releaser pheromone) of high potency, which is still part of the pheromone trail, is placed. This allows for recruitment by detection of its active space. After the trail is created the scout starts to forage by going back to the food location to retrieve food items by means of tropotaxis. After the scout forages for the first time (and returns to nest), it then proceeds from there on like a follower agent to continue the foraging process. The follower agents, on detecting recruitment pheromone by the edge of the nest, are excited and induced to leave the nest along the pheromone trail. Specifically, any of the follower agents that comes in contact with the recruitment pheromone and is in its active space, is induced to leave the nest to forage. When a follower agent leaves the nest, it makes use of tropotaxis to attempt to stay within the active space of the pheromone trail, therefore guiding it to the food location, where all that is left for it to do is to move accordingly. The agent moves through the trail and is guided by means of tropotaxis. When in the food location, it starts to randomly search for food. When food has been retrieved, it is then allowed to leave the food location. When the releaser pheromone is detected in the food location, the agent is induced to leave the food location, and is guided back to the nest along the pheromone trail via tropotaxis. When the agents retrieve food from the food location, they reinforce the pheromone trail, if it has decayed, back to max trail potency or size. When the food source gets exhausted or when the agents are not able to retrieve any food, the pheromone trail is not reinforced. When the pheromone trail decays below a threshold value or potency, any ant that detects it, is informed that the food source has been exhausted. This information allows all foraging agents in the food location to leave and go back to the nest. When the food source has been exhausted, the pheromone trail and the pheromone that marks out the food location decays until its gone, since there is no reinforcement. Tropotaxis is used to follow the pheromone trail, but when this is not successful, the agent goes back to the nest, since it’s the only location it knows, therefore, continuing the foraging process. When an agent enters a food location, it makes a choice of either going back to the nest with the pheromone trail or going back to the nest alone. When an agent goes back alone, it creates a new pheromone trail, which would help in improving the foraging. Although, the scouts and followers have a very high probability of going back to the nest with the created pheromone trail. The scouts have a higher probability than the followers to go back to the nest alone.

3.2.2.1.2. Compositions of the Novel Foraging Behaviour

This section discusses the base processes and behaviours that culminates to facilitate the novel foraging behaviour [see figure 9]. These processes are very similar to the ones observed in the foraging behaviour of natural ant swarms [see section 2.4], since this behaviour attempts to replicate it. These processes are described in the sub sections ahead according to how it works for the simulation experiments.

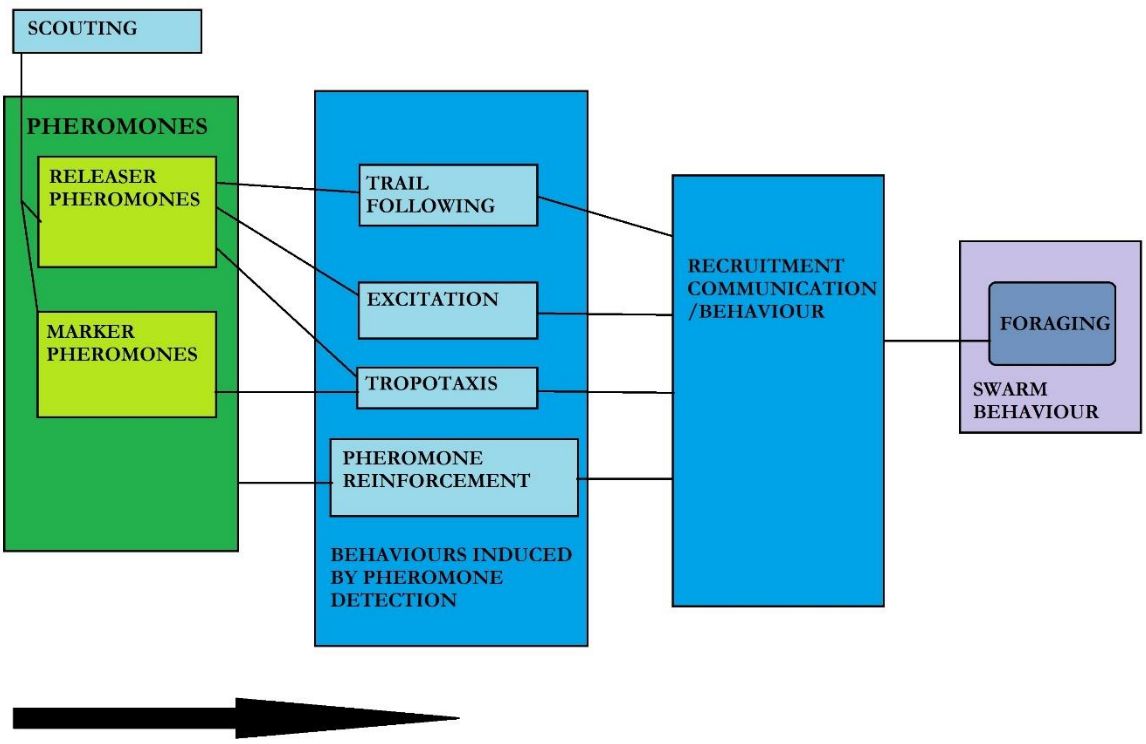


Figure 9. *Connections of the base behaviours and processes to facilitate the Novel foraging behaviour.*

3.2.2.1.2.1. Scouting

This is a behaviour that occurs in all scouts (leader agents). The scouts leave the nest to find a food source and initializes the foraging process by setting up the pheromone trail, food location marker pheromone, and recruitment/releaser pheromones. Until scouting is successful, foraging and recruitment does not occur. This sets up a chain reaction or emerged process of foraging by introducing the foraging swarm to a food source. This behaviour starts the foraging process but does not end it.

3.2.2.1.2.2. Pheromones

The pheromones of fire ants tend to have both recruitment and orientation effects and are generally termed Releaser pheromones. This type of pheromone induces the agents to perform certain actions like trail-following, movements, orientation etc. In the novel foraging behaviour described earlier, there are 2 types of pheromones that are used, and these are:

- Marker Pheromones: – these are pheromones that are used by the swarm (or queen) to mark out the nest location, and by the scouts to mark out the locations of food sources. They do not induce any action, but they are used to set boundaries. For example, In the simulation, when a scout encounters a food source, because of the simple nature of this simulation and the agents, it does not make any analysis on the size, benefits or distribution of the food in its current location. Therefore, without the ability of estimating the size of the food, a marker pheromone is used to set a boundary around the position it encountered the food source from. The marker pheromones used for marking out food locations or nest locations both have their default size or potency. The term "marker" pheromone is coined in this research to describe the pheromone currently explained, which are also observed in natural ant swarms.

- Releaser Pheromones: - these are pheromones that induces a behaviour in the agents. In the novel foraging behaviour, there are of two types: (a) Pheromone trails and (b) Recruitment pheromones

  (a) Pheromone Trails: – these are set of releaser pheromones, that induces the behaviour of trail-following, with the aid of tropotaxis. The active space is sampled by the left and right edges of the agents and used to move towards the centre. Once an agent is within these trails, they set their motion to forward movements and make adjustment to the left or right using tropotaxis.

  (b) Recruitment Pheromones: – these are releaser pheromones, that induces excitation to leave the nest or food locations. When the ants move randomly in either the nest or a food location, they can detect the active space of the releaser pheromones, which is linked to other pheromones that make up the pheromone trail. Therefore, when the agents are induced to leave the nest, they are directly linked to a pheromone trail, and then begin to advance to the next destination.

3.2.2.1.2.3. Behaviours Induced from Pheromone Detection (Stigmergy)

These are stigmergic behaviours that are induced on detection of pheromones. These behaviours culminate to allow the emergence of the novel foraging behaviour.

- Trail-following and excitation: - These are behaviours induced from the detection of releaser pheromones, which is either recruitment pheromones or pheromone trails. Excitation occurs when an agent is either within the nest or a food location and detects a recruitment pheromone. Therefore, inducing it to leave its current location to the outside environment or to go along the pheromone trail. Trail-following occurs when an agent is within the pheromone trail. By making use of tropotaxis to decode the concentrations of the pheromone trail, it makes movements that are observed as trail following.

- Tropotaxis: - This is a process that works with the trail-following behaviour, to allow for successful journey along the pheromone trail. This process is induced on detection of pheromone trails or marker pheromones and is performed with the edge positions of the agent's body. The concentrations of the pheromones that make up the pheromone trail are measured and decoded, and this depends on the agent's position within the pheromone trail and the decay of the pheromones. When the agents travel along the pheromone trail, they use tropotaxis to decode the pheromone concentration they sense from their position. This tells them their position within the trail and allows them to make adjustments as best as they can to remain within the active space. As these adjustments are made, they travel through the trail, and hopefully reach their destinations. In the case of marker pheromones, agents use tropotaxis to detect the boundaries the pheromone make, which is the edge of the pheromone, and make appropriate movement to stay within the area marked out by the pheromone.

- Pheromone Reinforcement: - This is a process that is induced by the pheromone trail when foraging. The agents reinforce the pheromone trail when food has been retrieved, by reinforcing the pheromone trail back to max size or potency when it has decayed over time. This acts as a regulatory mechanism that can halt the process of foraging, and also acts as feedback communication to all the agents in the swarm. There is a certain threshold for each type of pheromone (pheromone trail and releaser or recruitment pheromones). When these pheromone decay below their threshold value, the agents do not reinforce them again.

3.2.2.1.2.4. Recruitment Communication

From the behaviours induced by the pheromones and the interaction between them, a recruitment communication system is formed. This is very similar to the natural recruitment communication observed in natural ant swarms. This communication system observed from the novel behaviour, shows how the pheromone is used as a medium, where foraging emerges from the interactions of different induced behaviours. For as long as recruitment continues, foraging continues. The foraging process depends on the recruitment communication system, which depends on the reinforcement of pheromones. Pheromone reinforcement in turn depends on the richness of a food source and the rewards the agents get from the food source. Once there is no reward or positive feedback from the food source, the recruitment depreciates and foraging decreases, until it ends. The measure and communication of feedbacks are all done through the pheromone, and therefore, intelligent decision of halting the foraging process at the right time is accomplished.

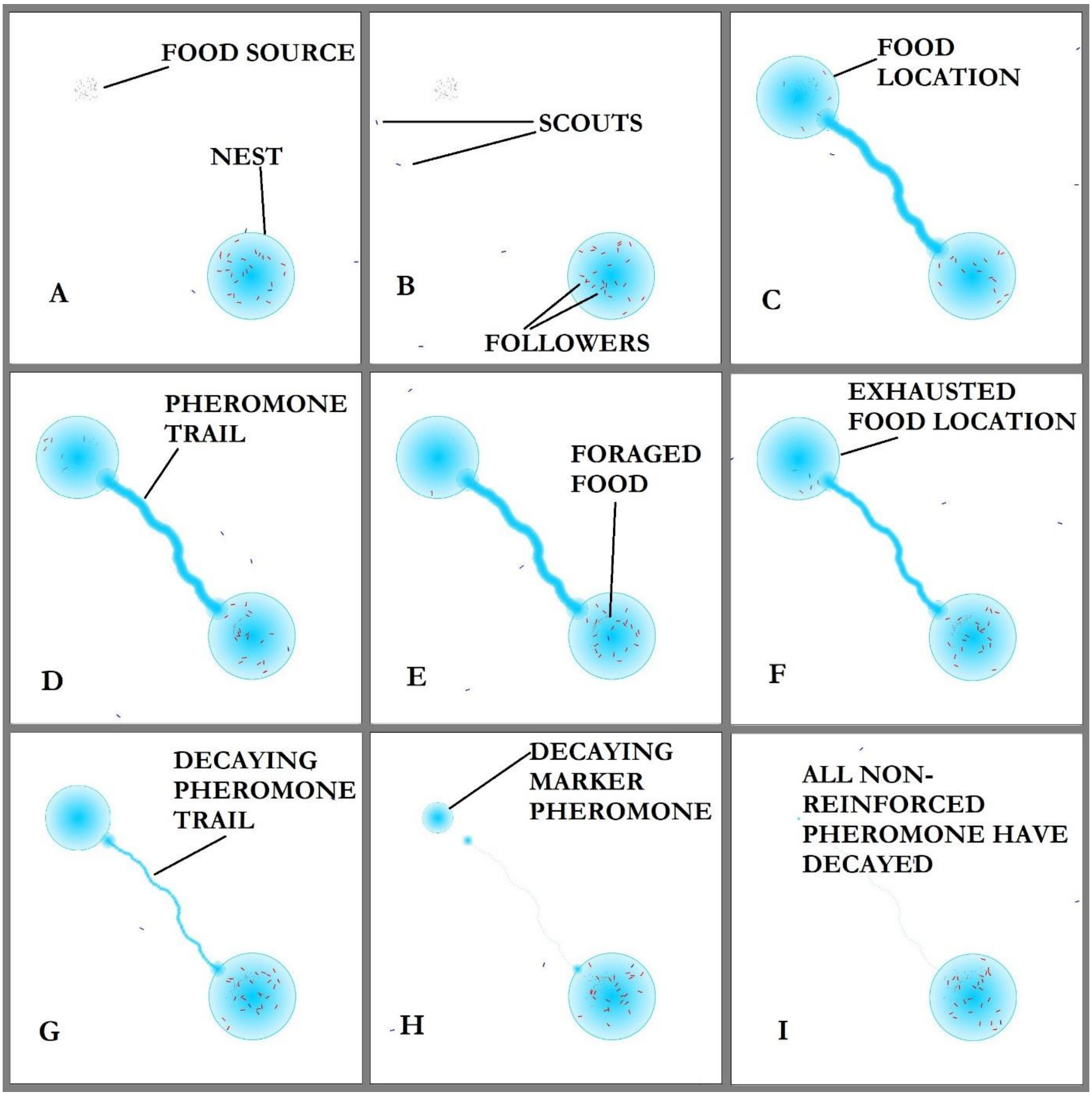


Figure 10. *Novel foraging simulation in world with a single food source and a nest. Swarm composition is made up of 25 followers and 4 scouts. (A) Scouts and followers initialised at random positions in the nest, (B) the scouts leave the nest and begin to search for a food source. (C) a food source is located, and the scout creates a pheromone trail as it goes back to the nest. (D) followers and the scout forage food from the food location and keep reinforcing the pheromone trail. (E) almost all the food has been foraged and dropped in the nest (F) the food source is exhausted, and pheromone trail is no longer reinforced. (G) the pheromone trail keeps on decaying linearly over time. (H) the food source's marker pheromone starts to decay as well, linearly over time. (I) all the pheromones decay till they are gone. Since there is no other food source, nothing happens, and the scouts with no food source found, keeps searching.*

3.2.2.2. Description of the Simulation of the Hybrid Foraging Behaviour

In this behaviour, the novel foraging behaviour is hybridized with the flocking behaviour of avian flocks. The novel foraging behaviour has been discussed in the previous section. In this section, the hybrid behaviour is discussed based on how it works in simulation. Apart from replicating the foraging behaviour of ant swarms (novel behaviour), this behaviour also attempts to replicate bird's flocking behaviour [see section 2.5], which is used to hybridize the trail following and recruitment behaviour of the novel foraging behaviour. The flocking behaviour is hybridized into the novel foraging behaviour; hence, some processes might differ or not be perfectly replicated due to limitations of the simulator. The term flocks and clusters are used interchangeably.

In summary, for the hybrid foraging behaviour, the scouts and the followers are initialized at random locations within the nest. The scouts leave the nest to look for a food source, while the followers move randomly in the nest. When a scout encounters a food source, it marks the location, places a releaser pheromone and creates a pheromone trail from there as it goes back to the nest. On reaching the nest, the scout recruits some followers by placing a recruitment pheromone and forms a cluster (flock) with them. This is going to be the first foraging expedition to be made. This cluster then travels along the pheromone trail to the food location to forage. When food has been retrieved by any of the agent (the scout or a follower), it forms a cluster with other agents that have retrieved food, and they travel through the pheromone trail back to the nest. After the first foraging expedition (excluding its return), new clusters are formed from the nest when followers detect the recruitment pheromone. After a cluster is formed, it travels along the pheromone trail to the food location to forage. When food has been retrieved in the food location, a returning cluster is formed by agents with food when the releaser pheromone placed at the edge of the food location is detected. The pheromone trail is reinforced in the going and coming of the clusters, but the recruitment pheromone in the nest is only reinforced when food has been retrieved. New clusters are formed in the nest and food location while the foraging task is being undertaken. These clusters can range from pairs to large groups of agents. Once the food source has been exhausted, the recruitment pheromone is not reinforced anymore, and clusters from the nest are not formed anymore. Therefore, halting the foraging process, due to the fact that the pheromones and pheromone trail would not be reinforced anymore, and therefore, decaying till they are gone.

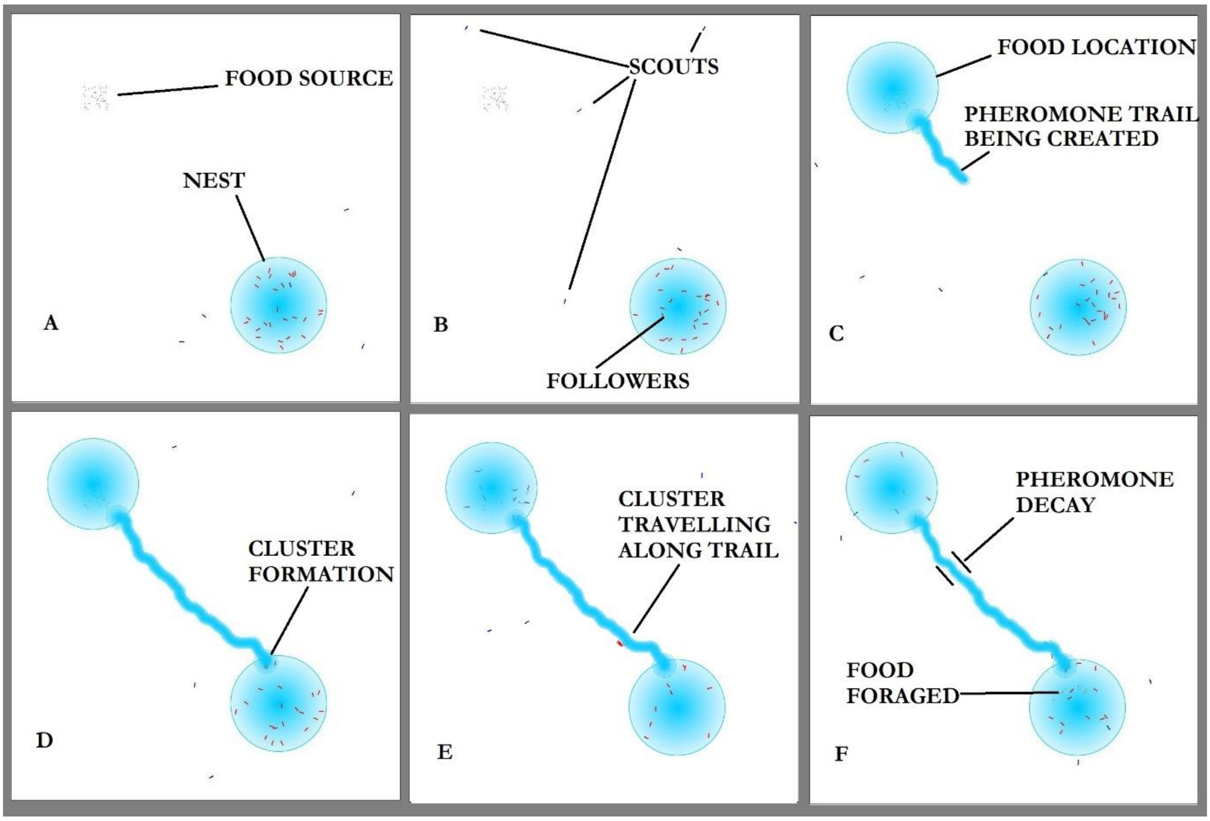


Figure 11. *Hybrid foraging behaviour in a world with a nest and a single food source. (A) scouts and followers are initialised in random positions within the nest, (B) scouts leave the nest to search for a food source, (C) a scout finds a food source, places a marker pheromone and a releaser pheromone, and creates a pheromone trail as it goes back to the nest. (D) the pheromone trail connects the food location and the nest. The first cluster start to form at the nest, with the scout being its first initiator, (E) the first cluster already in the food location, and a new cluster travels along the pheromone trail. (F) the pheromone trail decays linearly as time passes. Food foraged by returning clusters are in the nest location.*

3.2.2.2.1. Description of the Hybrid Foraging Behaviour

In more details, the scouts and the foragers are initialized at random positions within the nest. The scouts leave the nest to search for a food source, while the followers move randomly within the nest. When a scout encounters a food source, it places a highly-potent pheromone (marker pheromone), that marks out a boundary about the food source. The scout then begins to go back to the nest, and on the edge of the marker pheromone, it places a releaser pheromone of potency or size larger than that of the pheromones that will make up the pheromone trail. From the edge of the marker pheromone, it creates a pheromone trail as it goes back to the nest. If there are obstacles in its path, it avoids these obstacles, therefore, creating a safe path with the pheromone trail. On reaching the nest, just by the edge, it stops creating the pheromone trail, and places a recruitment pheromone in the nest, but just at the edge of the nest. While remaining in the position of placement of the recruitment pheromone, the scout waits for followers to detect the recruitment pheromone and enter its active space, in order to form a cluster (flock) with them.

For the creation of the cluster, the scout (including all other agents) consider the size of the agents in the swarm and the size of the recruitment pheromone to decide how much agents would be needed for the cluster. The recruitment pheromone decays (as well as the pheromone trail) linearly with time, and when the agents detect that the pheromone is decayed, the confidence in the food source is reduced, and therefore the number of agents needed for the cluster would reduce based on this and be decided based on the number of agents in the nest. All the agents have individual opinions on how much members are needed in the cluster. An example of this can be seen when an agent detects the recruitment pheromone when it has not yet decayed, therefore having the opinion that a large group of members would be needed, and another agent detects the recruitment pheromone when it has decayed, hence, having the opinion that a small group would be enough. Eventually it's the opinion of the first (current) initiator (current leader) that matters, and when its satisfied with the size of its group, it leads them out of the nest. Therefore, the real size of the flock of foragers might not be the size decided by the current initiator or decided by everyone in the flock but can be an average size based on every flock member's opinion.

After the cluster is formed, and while its being formed, the initiator (or leader) of the cluster is decided based on the position of the members of the cluster in the recruitment pheromone. When an agent detects the recruitment pheromone, and is in its active space, cluster formation and an orientation behaviour is induced. The current initiator (first initiator) of the cluster is decided based on which agent is in the inner active space, which is a position of highest pheromone just around the position of the pheromone placement. In the first foraging expedition, when the scout waits to form a cluster, since it's in the position of placement of the recruitment pheromone, it qualifies as the current initiator of the cluster. When the recruitment pheromone decays as it waits for flock members, the pheromone concentration sensed from its position can decrease as the active spaces of the recruitment pheromone reduces, and therefore can disqualify it from being the initiator. When a cluster is formed, and there is no qualified initiator, any agent that comes to join the cluster must place itself at a position that qualifies it as initiator, which is a position that is within the inner active space and has a higher pheromone concentration compared to the positions of the other flock members. If there is no initiator in the cluster being formed, due to decay of the recruitment pheromone, a new initiator must be present, before any foraging occurs. The first initiator is the initiator that leads the cluster out of the nest. As the cluster is formed, when an agent enters the active space of the recruitment pheromone, and joins the cluster, it orients based on the initiator's orientation. If there is no initiator, the agent can become the first initiator, and new flock members would orient based on its orientation.

When a cluster has been formed, and the first (current) initiator is satisfied with the number of members, it then leads the swarm out of the nest along the pheromone trail. During the first expedition, when the scout, which is the initiator, is satisfied with the number of the flock member, it leads them out of the nest, along the pheromone trail. During this process, another flock member might be in a position in the pheromone trail of higher pheromone concentration than the current initiator and any other flock member. This agent takes command as the initiator and begins to lead the flock along the pheromone trail. Therefore, before reaching the food location, multiple initiators would have taken command. When the flock successfully reaches the food location, all the flock members disperse and leave the flock, then starts to search for food.

When food is retrieved, the agents with food form a returning flock that goes back to the nest. The first initiator of flocks (clusters) is normally the first agent that arrives at the releaser or recruiting pheromone. On detection of the releaser pheromone in the food location, if there is no current flock forming, any agent that has food, would go to the inner active space, and become the initiator. New flock members would stop at positions within the active space and orient based on the initiator's orientation. If there is no current initiator due to pheromone decay, this would allow a new flock member to place itself in the inner active space and take command as initiator. The flock formed at the food location also depends on the number of agents in the food location and the size of the releaser pheromones. Once the initiator is satisfied with the size of the flock, it leads them out of the food location along the pheromone trail. During this process, flock members can take command as the new initiator, as far as they are in a position within the pheromone trail with the highest concentration compared to the rest of the flock members. On reaching the nest, multiple initiators would have taken command, and the flock members would disperse and leave the flock and drop the food retrieved in suitable positions.

Flocks (clusters) are formed in the nest and in the food location, as long as food remains in the food location. This is due to the fact that when the flocks leave the nest or the food location, the pheromone trail is always reinforced. This accounts for the time taken in forming flocks, where pheromone trails decay along with it. When members of the flock retrieve food and they detect the recruitment pheromone while heading to the nest, and notice that its decayed, they reinforce it. Any flock member that can detect the pheromone trail (initiator or not), and finds out that a pheromone is decayed, reinforces it. These processes continue the foraging process, but when a food source is exhausted, the recruitment pheromone is not reinforced anymore, and eventually no flock would be formed from the nest. As time goes by, when the recruitment pheromone decays below a threshold, no flock is formed from the nest anymore. All returning foragers would not reinforce the recruitment pheromone again, due to the exhaustion of the food source or no food retrieval.

When a foraging flock reaches a food location, all of them make a choice of either following the trail back to the nest or creating a new trail and making the journey alone. There is a high probability that the scouts and the followers would follow the trail when returning to the nest, but the scouts have a higher probability of returning to the nest alone than the followers. This allows new pheromone trails to be created, therefore improving the foraging process.

Sometimes when a flock is formed, the members would have diverse opinions on the size of the flock, and therefore would recognise only some specific agents as members of the flock. This results to the flock members recognizing different flock mates as members of the flock, and not recognising the other. In these situations, when an agent has none of the members of its recognised flock in a position of pheromone trail detection, the agent leaves its flock and returns to the nest. Some agents with a small number of recognised flock mates, which might be part of the initiator's recognised flock, but are not in position of pheromone detection, would have to return to the nest if they are not in a position of pheromone detection. In general, when an agent see that its flock is not suitable, it leaves and goes back to the nest.

When the flock travels through the pheromone trail, the initiator in the flock leads the flock member by using tropotaxis to guide itself along the pheromone trail. The flock members monitor the initiators movements and make movements according to the initiator's. Since the initiator is the agent in the best position along the pheromone trail, it is qualified as the flock's leader, which is temporary, until another agent with better position within the pheromone trail arises. When the flock travels along the pheromone trail, redundancies can be observed, as these flock members depend on themselves, and make decisions as a unit that depend on the initiator. Behaviours that can be observed, which were briefly described in [32], are profiting and cooperation.

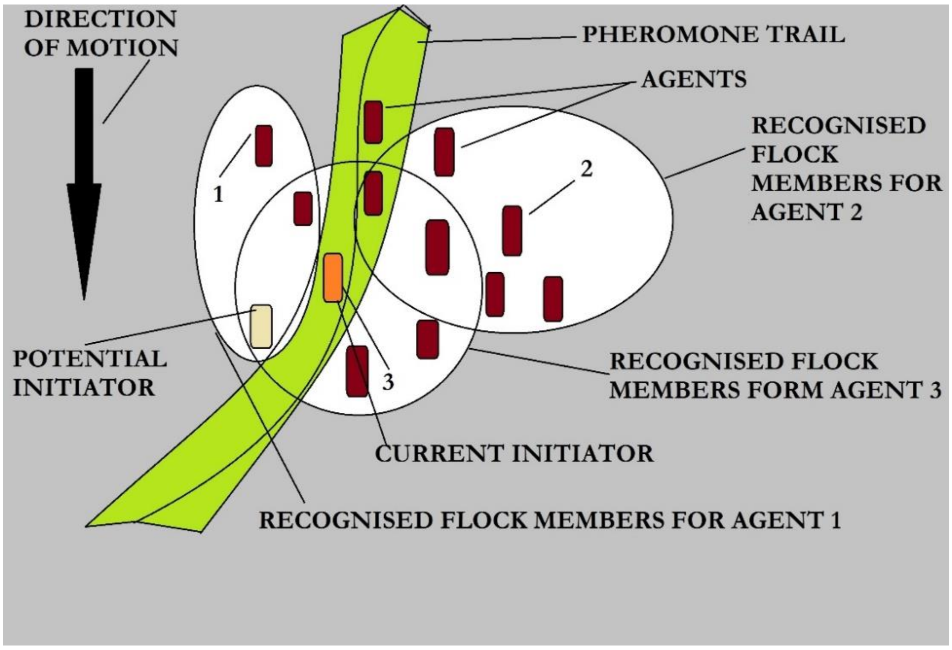


Figure 12. *An example of a cluster (flock) scenario. This cluster is moving from the nest to the food location. When it was formed, agent 1, 2 and 3 recognised the agents in the circle as its flock member, due to different times in which they joined the flock and its opinion on the needed number of flock members. Given the situation portrayed, agent 1 would return to the nest, because it notices that none of its flock members are detecting the pheromone trail. Agent 2 will remain in the flock because it notices that one of its flock members is detecting the pheromone, and it takes the agent as the initiator, and observes its movement. Majority of the flock members that are not at the edge of the flock, might recognise almost everyone in the flock as its flock members. There can be extreme scenarios, where this situation gets worse and the flock would disband, especially when the recognised flock members of each member are very different.*

3.2.2.2.2. Compositions of the Hybrid Foraging Behaviour

In this section, the base behaviours and processes that facilitates the hybrid foraging behaviour are discussed. Some new behaviours that are observed are also discussed. Most of these behaviours and processes have been discussed in section 3.2.2.1.2, therefore, only new properties or effects of these behaviours and processes are discussed.

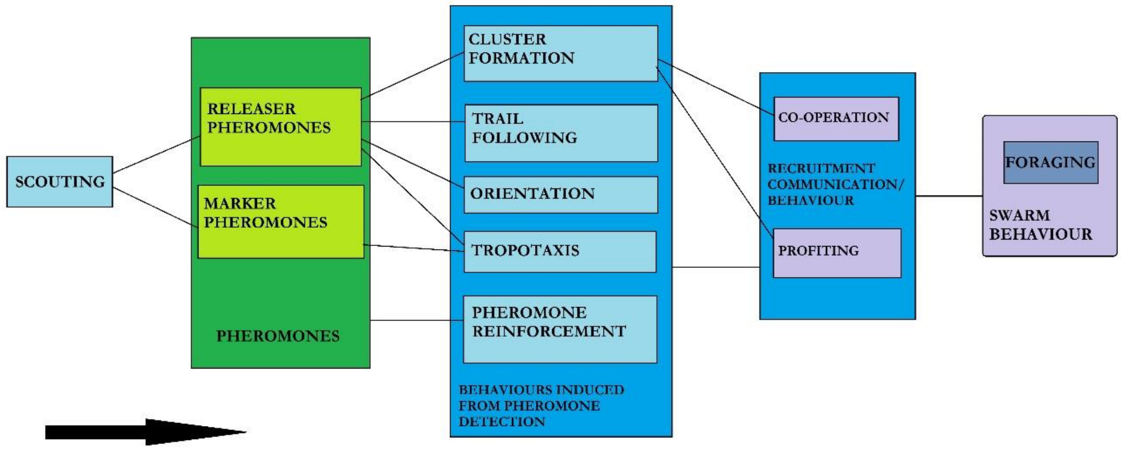


Figure 13. *Connections made by the base processes and behaviours that help facilitate foraging.*

3.2.2.2.2.1. Pheromones

The pheromones of fire ants tend to have both recruitment and orientation effects and are generally termed Releaser pheromones. There are 2 types of pheromones that are used, and these are: (a) Marker pheromones and (b) Releaser pheromones. In this foraging behaviour, the releaser pheromones induce an additional behaviour of orientation. This behaviour is discussed in the next section.

3.2.2.2.2.2. Behaviours Induced from Pheromone Detection (Stigmergy)

These are stigmergic behaviours that are induced by the detection of releaser pheromones. Releaser pheromones make up the pheromone trail and recruitment pheromone that are used in this foraging behaviour. A releaser pheromone is also used in the food location, to serve a similar function like that of the recruitment pheromone. The behaviours and processes discussed in this section are simple behaviours that inter-play with each other to facilitate the hybrid foraging behaviour.

- Cluster (flock) formation: - This behaviour is as a result of the hybridization. It occurs when agents detect the active space of a releaser pheromone from the nest or a food location. This induces an agent to stop after detection of the active space, and to recognise other agents in the active space as flock members. As seen in the description given earlier, when a cluster is formed, potential flock members check to see if there is an initiator, which is to check to see if any agent is in the inner active space. When there is no initiator, an agent would have to detect and stop in the inner active space to be part of the flock (cluster), by taking charge as the initiator.

- Orientation and Alignment: - orientation is performed during cluster formation. It also occurs when agents detect the active space of a releaser pheromone. After the agents recognise the initiator in the swarm, they orient based on the initiator's orientation. Alignment or orientation also occur when the flock members observe and perform the initiator's movements while travelling along the pheromone trail

- Trail-following: - This behaviour is undertaken by the initiator of a flock. When the initiator leads the flock through the pheromone, it uses tropotaxis to guide itself along the pheromone trail, therefore performing trail-following. Since the role of initiator depends on the positions of flock members in the pheromone trail, multiple initiators are always likely to arise when a flock travels along the pheromone trail. Therefore, the behaviour of trail following can be perform by multiple flock members as they journey to and from the nest and a food location.

- Pheromone Reinforcement: - This behaviour is induced during foraging, when pheromone trail or releaser pheromones are detected, and have decayed. When the pheromone trail decay, despite where the agents are coming from or going to, they are reinforced. The recruitment pheromone is only reinforced by returning flocks that have successfully retrieved food from a food location. There is a certain threshold for each type of pheromone (pheromone trails and releaser or recruitment pheromones). When these pheromone decay pass their threshold value, the agents do not reinforce them again.

3.2.2.2.2.3. Behaviours observed from hybridization

- Profiting: - Profiting is a phenomenon of individuals forming groups to increase their own reproductive success [32]. Individuals that manage to profit from the behaviour of others perform better [32]. Only agents who profit would forage, and in the end they all profit from each other, resulting in cooperation [32]. This is more likely if the sum of fitness of the flock increases if the individuals profit from each other [32]. Profiting can be observed when members of the flock profit from the initiator's trail-following behaviour. For example, some flock members might not have the current initiator as its recognised flock members, but one of its recognised flock members might. If any of it recognised flock member is in position of pheromone detection, the agent would see that flock member as the initiator and profit from it. The recognised flock member that is seen as initiator, might be profiting from the true current initiator of the whole flock. This case is very likely to occur in agents positioned at the edge of the flock. Even though its recognised flock is not suitable for the journey, it is still able to make it to the food location, by profiting from its recognised flock members.

- Cooperation: - Cooperation can be defined as any adaptation of agents to certain constraints or rules in order to increase the success of its cooperating members. The current initiator of a flock performs tropotaxis and exhibit a trail-following behaviour, which is monitored by its flock members in order to travel according to the pheromone trail's guidance. Cooperation is observed when agents notice that they are in the best position to lead the flock, by observing their position in the pheromone trail and the pheromone concentration sensed, and then taking command as initiator. Multiple initiators arise due to this situation, and the flock cooperate by - relinquishing the initiator position, taking command of the initiator position, and obeying and observing the actions of the initiator. Each agent cooperates with its flock mates in order to successfully travel along the pheromone trail and make it to the food location.

3.2.2.2.2.4. Recruitment Communication

From the interplay between the behaviours and processes in the hybrid foraging behaviour, a more complex recruitment communication system emerges. Recruitment takes place both in the nest and in the food locations, as these agents are induced to form flocks, which travels along the pheromone trail to the next location. Recruitment is halted when the recruitment pheromone in the nest decays below a certain threshold. Once recruitment is halted, foraging is also halted. More complex processes and behaviours are involved in this recruitment communication, as described above.

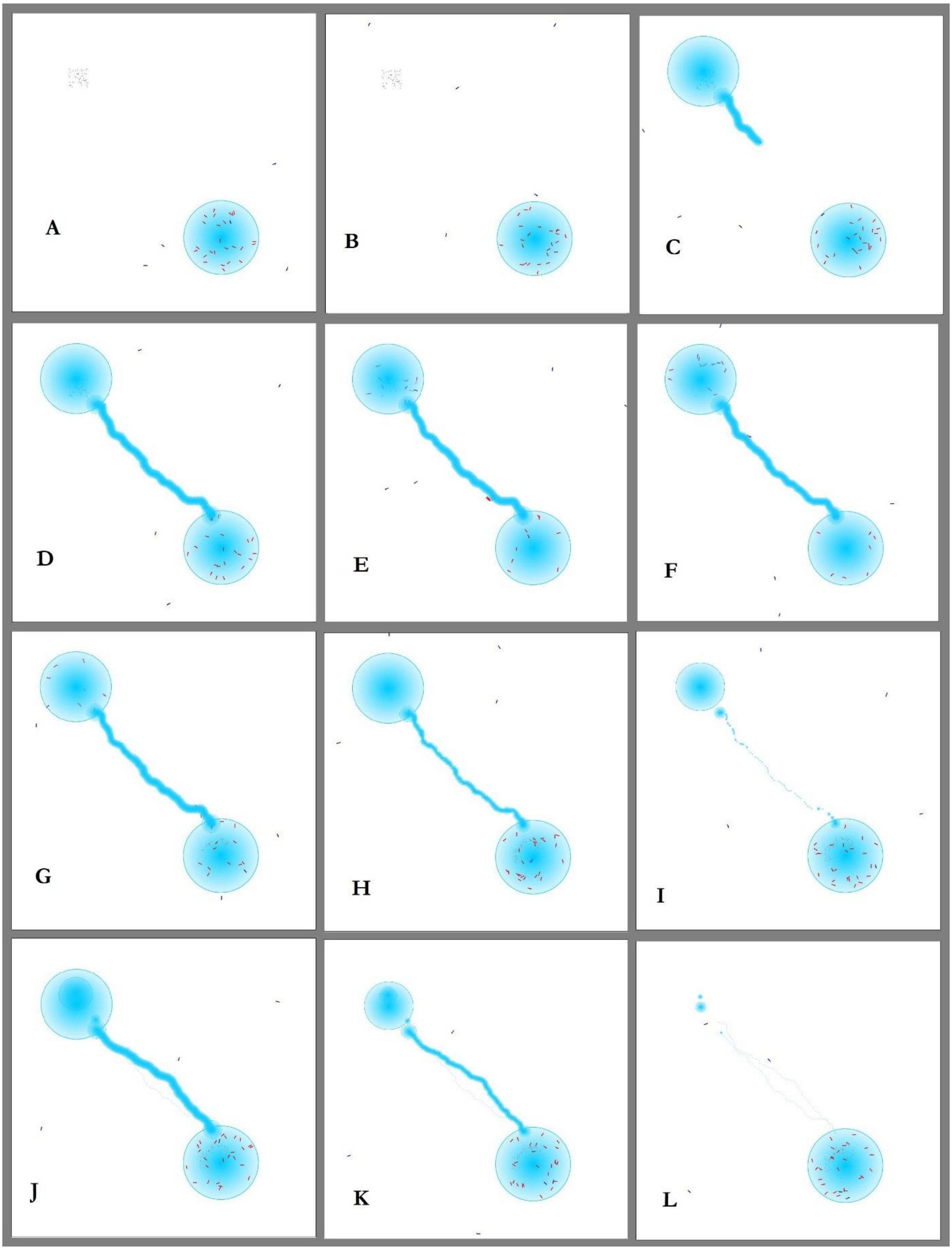


Figure 14. *Hybrid foraging Behaviour in a world with a nest and a single food source. (A) scouts and followers are initialized at random positions within the nest, (B) the scouts leave to search for food, (C) a scout finds a food source, marks the location and creates a pheromone trail as it goes back to the nest (D) the pheromone trail connects the nest and food location. The first cluster starts to form in the recruitment pheromone in the nest. (E) the first cluster already in the food location, and a new*

cluster travels along the pheromone trail, (F) returning cluster going back to nest with food retrieved, (G) the food foraged are in the nest (H) exceptional situation where not all the food in the food location has been foraged, and the pheromone trail decays below threshold, (I) the food source marker pheromone, and pheromone trail decays, (J) a scout locates some food that was not foraged, and begins the foraging process again, (K,L) since the food left are not much, foraging ends quickly and food source marker pheromone and pheromone trail decays until they are gone.

3.3. MODELS AND ALGORITHMS

In this section, the algorithms that replicate and implement the behaviours and processes of both the novel foraging behaviour and hybrid foraging behaviour, which were described in 3.2, are provided here and briefly discussed. The environments (worlds), attributes of the environment, and the agents are modelled for both the experimentation of the novel and hybrid foraging behaviour. These are referred to as Base models. Base models describe the design and development of scenarios and agents that facilitate the working of the novel and hybrid foraging behaviour.

3.3.1. Base Models

For both foraging behaviours, the agents used are modelled to have some capabilities and decision making. These are defined by the decision variables that they are designed to have, therefore enabling the agents to perform foraging as described in 3.2. The pheromones are also modelled based on the descriptions given in 2.4. The world is modelled so that experiments are conducted in regard to the research questions. This section discusses how the agents, pheromones and the world are set up to enable the implementation of the novel and hybrid foraging behaviour. These base models are – (a) the world model, (b) the pheromone model, and (c) the agent model.

3.3.1.1. The World Model

The world is set up such that the research questions can be answered by simulating the novel or hybrid behaviour in it. As seen in section 3.2.2, the world is a 2-dimensional 800x800 pixel environment and there are four world scenarios, which are modelled to contain, a nest, food sources and sometimes obstacles. These are described ahead:

- <u>Nest</u>: This is an area in the environment that is marked out using a marker pheromone of an approximate size of 200x200 pixel. This size is constant and does not change regardless of the size of the swarm. The concentration from the centre, which is the point of placement, to the edge of the pheromone is a gradient from 1 to 0, where it gets higher as one approaches the centre and gets lower, when one approaches the edge.

- Obstacles: These are green square objects that are place between food sources and the nests. They are of 100x100 pixels and four of them are placed in the environment.

- Food Sources: These are locations that contain food items. A single food item is a brown 2x2 pixels square object. A food source would always have 50 food items that are randomly distributed within a 50x50 pixel space.

Using the attributes or objects that make up the world, four instances are provided as seen in figure 15.

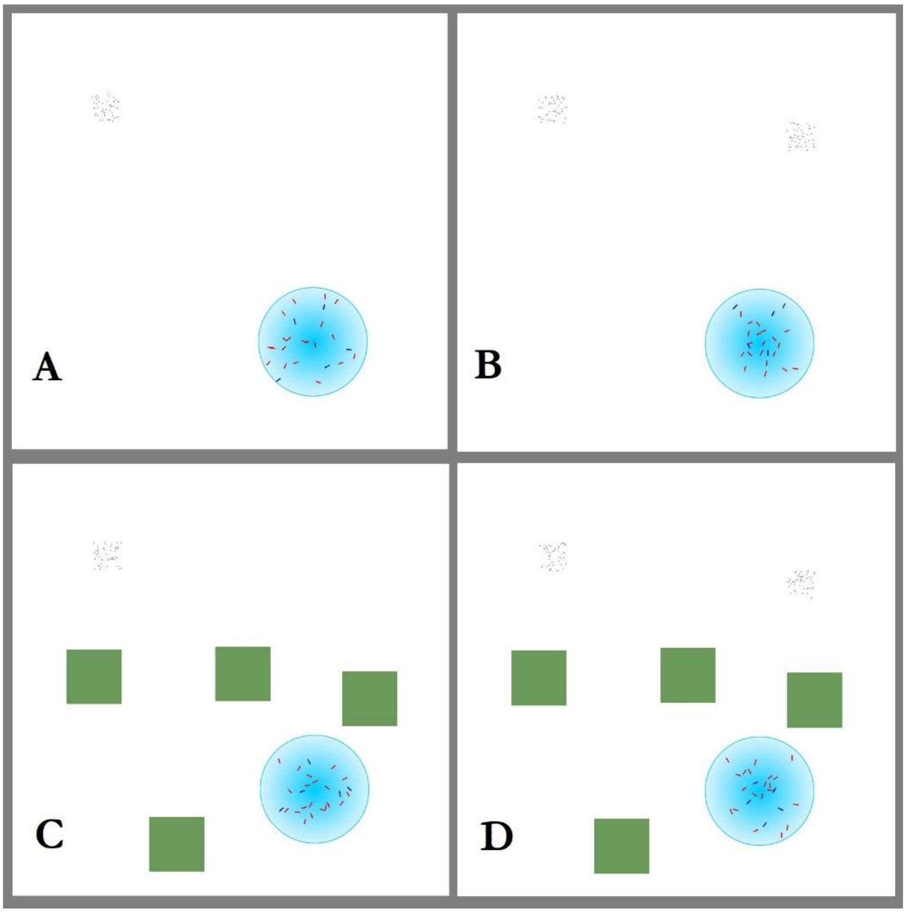


Figure 15. *The four world scenarios: (A) Open-Spaced world- one nest, one food source. (B) Multiple food filled world – one nest, two food sources. (C) World filled with obstacles – one nest, single food source, and four obstacles. (D) Multiple food with obstacles in world – one nest, two food sources, and four obstacles.*

3.3.1.2. The Pheromone Model

This section describes the pheromone model, which are placed in the environment to facilitate stigmergy. A pheromone is a circular structure, in which the centre is the point of placement, and from there to the circumference determine its radius (area of effect). The pheromone concentration increases along the radius, from the circumference position to the centre of the circle. As pheromone decay, the circle size reduces (diameter, radius and circumference). The pheromone concentration now gets calculated from this new size.

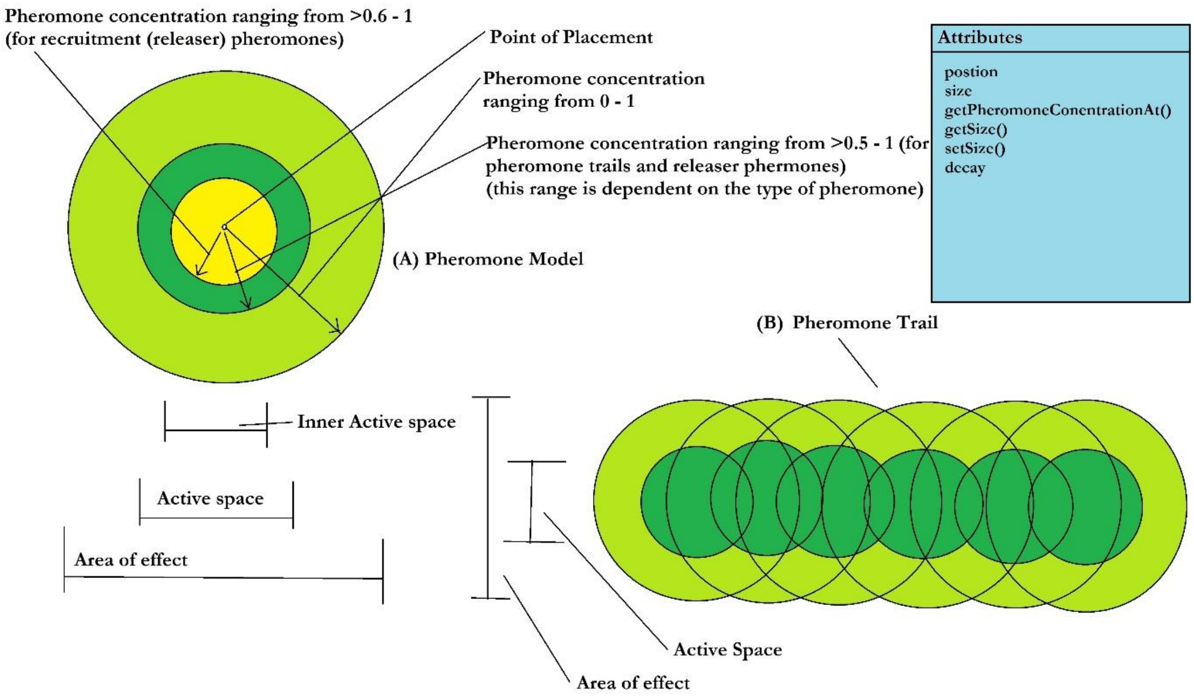


Figure 16. *Pheromone model and the pheromone trail. (A) this shows the structure of a pheromone, where the inner active space applies to recruitment (releaser) pheromones because they are used for cluster formation in the hybrid foraging behaviour. (B) pheromone trail structure shows how pheromones can be placed in order to form a trail.*

- Marker Pheromones: There are two use cases for this pheromone. The food source marker pheromones are of an approximate 190x190 pixels, while the nest marker pheromones are of an approximate 200x200 pixels. Marker pheromones do not induce any behaviours in their active space, but when food is foraged back to the nest, agents drop food items around the active space of the marker pheromone. Ideally, the queen would be located in the centre, and would be able to access the foraged food.

- Releaser Pheromones: These are used in the food location and nest, to induce agents to leave its current location and go along the pheromone trail. They are of approximately 50x50 pixels. As shown in figure 16, the inner active space is present in all pheromones, and it is only used in the hybrid foraging behaviour, during cluster formation.

- Pheromone Trail: these are used to connect food locations to the nest. It acts as a safe guide for all the foragers. The pheromones that make up the trail have an approximate size of 25x25 pixels.

3.3.1.2.1. Attributes

All the attributes regarding pheromones are not mentioned or discussed in this section, but the important attributes that are extensively used in both novel and hybrid foraging behaviour are presented below.

- Position: - pheromones are deposited at specific positions. These positions can be accessed by agents.
- Size: - when a pheromone is placed by an agent or during initialization, its size is set in pixels.
- getPheromoneConcentrationAt(Position): - Given the different types of pheromones described earlier, agents have to decode the pheromone concentration of its position within a pheromone's area of effect.
- getSize() :- This function is used by agents to monitor the size of pheromones, as its size is returned when called.
- setSize() : - This function is used to reinforce (or reset the size of) a pheromone when it has decayed.
- Decay: - This is an attribute that is common with all pheromones, except the nest marker pheromone. For novel foraging behaviour, a trail pheromone's size reduces by 3 after every 2000-time step. For Hybrid foraging behaviour, a trail pheromone's size reduces by 3 after every 3000 time-step.

3.3.1.3. The Agent Model

This section describes how the agents have been modelled. The attributes, decision variables and memory variables, which facilitates the actions that an agent can perform are discussed in this section. An agent attempts to replicate a fire ant, and figure 17 shows the components that makes up the agents.

3.3.1.3.1. Memory Variables

These are variables that store information like positions, list of fellow agents etc. With this information stored in the memory, an agent can make intelligent decisions. These variables are discussed in this section [see figure 17].

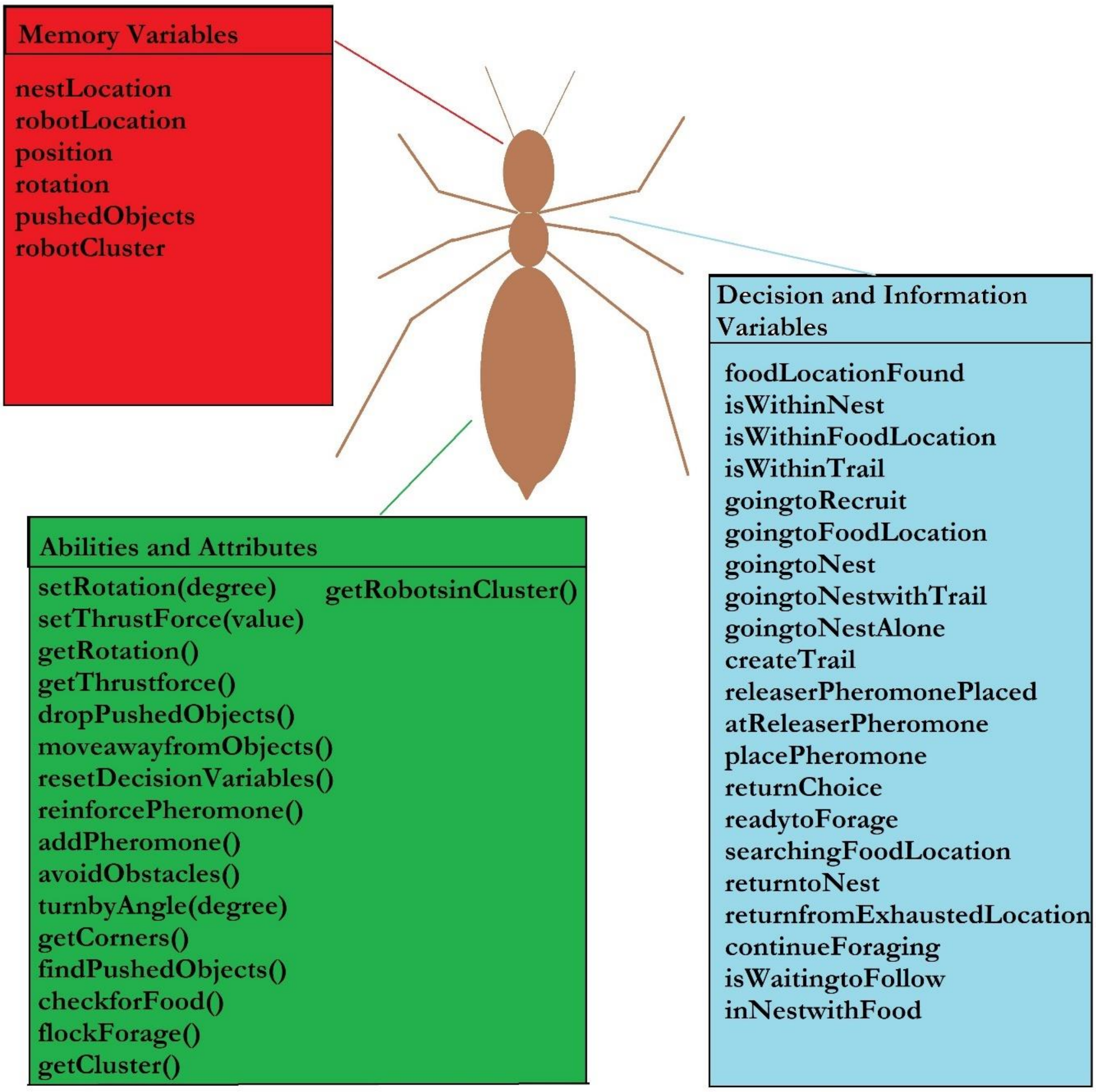


Figure 17. *The model of an agent.*

- nestLocation: - This is a variable that stores a position which gives a general idea of the nest location, and it is not the same for every agent. An agent is always initialised at a random position within the nest, and this position is recorded in this variable.
- robotLocation: - This variable is used to store the position of an agent whenever needed. It can be used to refer to the agent's last stored previous location, in order to perform various tasks, like the laying of pheromone trail.

- position: - This variable always holds the current position of the agent. Since the environment is a 2D space, position is in the format – [x, y].
- rotation: This variable always holds the current rotation (degrees) of the agent.
- pushedObjects: - This is an array list that tells the agent the objects (food or agent) it comes in contact with. This is used to register all the food items an agent comes in contact with, which would enable the agent to carry them.
- robotCluster: - This is used in hybrid foraging behaviour, an array list that registers the agents that are present within the active space of the releaser pheromone during cluster formation. This allows an agent to be able to recognise its flock member.

3.3.1.3.2. Decision and Information Variables

These are boolean variables that are used to store true or false information, in order to facilitate decision making. At initialization, all variables are set to false.

- foodLocationFound: - If an agent is a scout, this variable stores a true when a food source has been found. If an agent is a follower, this variable stores a true when it detects the active space of a recruitment pheromone from the nest, therefore telling it that a food source has been found. For the follower agents, this stores a false when it returns to the nest after successful or unsuccessful foraging.
- isWithinNest: - This variable stores a true when an agent is within the nest, and a false in the opposite case.
- isWithinFoodLocation: - This variable stores a true when an agent is within the food location, and a false in the opposite case.
- isWithinTrail: True, when an agent is within the pheromone trail, and false in the opposite case.
- goingtoRecruit: - Used by scouts. True, when a food source has been found and the marker pheromone has been placed. Allows the scout to return to the nest. This stores a false when a recruitment pheromone has been placed in the nest.
- goingtoFoodLocation: - True, when an agent has been recruited from the nest and it's to travel along the pheromone trail to the food location. When a scout finds food, and goes to the nest to recruit, by placing the recruitment pheromone, this variable sets to true, then it begins to travel along the pheromone trail back to the food location. When the agent is within a food location, this stores a false.
- goingtoNest: - True when an agent has retrieved food from the food source, and then detects the active space of the releaser pheromone at the food location.
- goingtoNestwithTrail: - When an agent enters a food location and chooses to return to nest using the pheromone trail after it has retrieved food, this variable stores a true.
- goingtoNestAlone: - When an agent enters a food location and chooses to return to the nest on its own, without using the pheromone trail, this variable stores a true.

- createTrail: - Used by scouts. When a scout finds a food source, and then places a food source marker pheromone, this variable stores a true. This allows the scout to place a releaser pheromone at the edge of the marker pheromone, and after this is done, this variable stores a false.
- ReleaserPheromonePlaced: - This is used when a scout creates a pheromone trail. When the recruitment pheromone has been placed in the nest, this stores a true. When the scout begins to go back to the food location to forage, this stores a false.
- placePheromone: - As an agent decides to return to the nest alone after food has been retrieved, when it's at the edge of the marker pheromone, this variable stores a true. This allows the agent to place a releaser pheromone and create a pheromone trail as it goes back home.
- returnChoice: - This stores a true when the choice of either going back to the nest with the pheromone trail or going back to the nest alone has been made.
- readytoForage: - This stores a true when an agent detects the active space of the recruitment pheromone. When it is induced to leave the nest and starts going to the food location, this variable stores a false.
- searchingFoodLocation: - When an agent enters a food location, this stores a true, and when an agent leaves as it goes to the nest, this stores a false. This allows agents to search the food location for food items.
- returntoNest: - when an agent does not successfully travel along (within) the pheromone trail to either the food location or the nest, this stores a true. If an agent cannot travel along the pheromone trail successfully, it gets lost, and the best thing to do is to return to the nest. This stores a false, when the agent has reached the nest.
- returnfromExhaustedLocation: - When an agent is in the food location, and it detects that the releaser pheromone has decayed below threshold, it's informed that the food location has been exhausted, and this variable stores a true. When the agent is within the nest, this variable sets to false.
- continueForaging (returntoCollectFood): - When a scout returns to the nest, this stores a true. This helps to continue the foraging process after successful or unsuccessful expeditions of the scout. When the active space of a recruitment pheromone in the nest is detected, this stores a false.
- isWaitingtoFollow: - Used by followers. When a follower has been recruited, this stores a true, and stores a false when its in the food location.
- inNestwithFood: - when an agent has retrieved food, and is within the active space of the nest, this sets to true.

3.3.1.3.3. Abilities and Attributes

This section describes what an agent can do. These are functions that perform one action or the other. The decision variables described earlier enables the intelligent implementation of these abilities or attributes in the required time.

- setRotation(degree): - This function rotates the agent by the specified degree given in the function parameter [36].

- setThrustforce(value): - This function allows an agent to move to a next location, depending on the value given in the parameter. Max value is 1, and min value is 0 [36].
- getRotation(): - This is used mostly in hybrid foraging behaviour when an agent in a cluster observes an initiators movement. This function returns the current rotation of the referenced agent [36].
- getThrustForce(): - Used mostly in hybrid foraging behaviour when an agent in a cluster observes an initiator's movement. This function returns the current thrust of the referenced agent [36].
- dropPushedObjects(): - this is used by an agent to drop all carried/pushed objects (food) [36].
- moveawayfromObjects(): - this allows the agent to move in opposite direction when it collides with an object. This is used when scouts find a food source but it's already been located, hence they move in opposite direction from the food source [36].
- resetDecisionVariables(): - this is used to reset the decision variables. This is used when an agent returns to the nest, hence restarting the foraging process.
- reinforcePheromone(): - this reinforces pheromones when used. To reinforce pheromones, this function sets the decayed pheromone back to its max size.
- addPheromones(): - when new pheromones are placed, this is called to create the pheromone, and add to the world.
- avoidObstacles(): - this uses the top left and top right positions of the agent's body to determine if there is an obstacle, hence making an appropriate movement to avoid the obstacle.
- turnbyAngle(degree): - turns an agent by a degree, as specified in the function's parameter [36].
- getCorners(): - this returns the current positions of the top left and right, and bottom left and right part of an agents body [36].
- findPushedObjects(pushedObjects): - this is used when an agent is in a food location. This function allows an agent to notice when it's in contact with food and adds this food to its list of pushed objects, therefore allowing it to carry the food as it moves [36].
- checkforFood(foodsourceMarkerPheromone): - this uses the food source marker pheromone of a food location where the agent is in, to check if food is still remaining in the food location. It returns true if food remains, and false if it doesn't.
- flockForage(): - This is used by an agent in a flock (cluster) to make appropriate movements according to the flock's current initiator.
- getRobotsinCluster(): - This is used during flock formation by an agent in the active space of the recruitment pheromone to get a list of robots that are also in the active space of the recruitment pheromone, that will make up its recognised flock member requirement.

3.3.2. Novel Foraging Behaviour

The flow charts presented in the appendix 8.2, which are 63 and 64, show the novel foraging algorithm. The novel foraging behaviour algorithm is described for both scouts and followers because of the differences in their behaviours and functions.

3.3.3. Hybrid Foraging Behaviour

The flow charts presented in the appendix 8.2, which are 65 and 66, show the hybrid foraging behaviour algorithm. The novel foraging behaviour algorithm is described for both scouts and followers because of the differences in their behaviours and functions.

3.4. EXPERIMENTS

In this section, the experiments that were conducted are presented. These experiments are classified as: (a) Open World experiments - given an open world space with no obstacles, a nest and one or two food sources, experiments on the novel and hybrid foraging behaviours are conducted, and (b) Obstacle World experiments - Given a world filled with obstacles, a nest and one or two food sources, experiments on the novel and hybrid foraging behaviours are conducted. Each experiment for the novel and hybrid behaviour is conducted with 100 simulation runs. As a result, a total of 48 experimentations (4,800 simulations) are conducted. These experiments are conducted to observe the following: (a) the number of food items foraged, (b) the time taken to completely exhaust a food source if possible, (c) the number of times pheromones were reinforced while foraging, (d) The number of times a food source is completely exhausted in an experiment with respect to the number of all attempted forage, (e) the number of times pheromones are reinforced while foraging to completely exhaust a food source. These are used to answer the research questions given in 2.7. The next chapter presents the results of these experiments and their analyses.

Table 1. *Simulation Experiments*

Experiments	**Open-World Experiments**	**Obstacle-World Experiments**
1	1 leader, 10 followers and 1 food source	
2	1 leader, 30 followers and 1 food source	
3	1 leader, 50 followers and 1 food source	
4	3 leaders, 10 followers and 1 food source	
5	3 leaders, 30 followers and 1 food source	
6	3 leaders, 50 followers and 1 food source	
7	1 leader, 10 followers and 2 food sources	
8	1 leader, 30 followers and 2 food sources	
9	1 leader, 50 followers and 2 food sources	
10	3 leader, 10 followers and 2 food sources	
11	3 leader, 30 followers and 2 food sources	
12	3 leader, 50 followers and 2 food sources	

Chapter 4

RESULTS AND ANALYSIS

This chapter presents the results gotten from the experiments conducted in the simulations. These results are presented in graphs. Thereafter, analysis of these results is presented. The analysis of the results would provide answers to the research questions presented in chapter 2.

4. RESULTS AND ANALYSIS

This chapter present the results of the experiments conducted. These results are correlated with the research questions, and the answers are induced from the results in the analysis section. The results are also analysed to provide a conclusive result of the experiments. Since the experiments were only conducted in simulations, the results would help to predict results of future hardware implementations. The results are divided into two main parts as can be inferred from the experiments: (a) Open World Results – present results of experiments conducted in an open spaced world, and (b) Obstacle World Results – present results of experiments conducted in a world filled with obstacles.

4.1. RESULTS

The results of the experiments are given in this section. Tables are created to contain the results based on the descriptions given below and are provided in the appendix [please see Appendix 8.1]. The graphical representations of these results are also provided ahead. Each experiment is made up of a 100 runs of 5 minutes duration. The results are presented based on the following:

(a) General Results –this includes simulation results where foraging from a food source can end when the food source is either incompletely or completely exhausted. The results presented from this scenario are [see appendix 8.1]:

- Number of foods foraged: - given the time span, this is the average number of foods foraged from the runs in an experiment.
- Number of times pheromones are reinforced: - given the timespan, this is the average number of times pheromones in the pheromone trail are reinforced while foraging from the runs in an experiment.
- Number of foods foraged (Successful forage only): - This presents an average number of foods foraged from runs with successful foraging. Because sometimes even though a scout finds a food and lays the trail, no single food is foraged due to different circumstances. These results to unsuccessful forage in simulation runs.
- Number of times pheromones are reinforced (Successful forage only): - presents the average number of times pheromones in the pheromone trail are reinforced while foraging, for runs with successful forage.

(b) Complete Forage Results: this includes simulation results where foraging from a food source (or two food sources) must have a food source completely exhausted. The results presented from this scenario are [see appendix 8.1]:

- Time taken for Complete forage – this is the average amount of time taken, in time-steps, to completely exhaust a food source while foraging, from the runs with complete forage of a food source in an experiment.
- Number of times pheromones are reinforced – this is the average number of times pheromones in the pheromone trail are reinforced for a food source to be exhausted. This can also be seen as the amount of work exerted during a complete forage of a food source.
- Number of times complete foraging occurs (occurrence): this is a percentage of how much times complete forage occurs in a given experiment. Each experiment has a 100 simulation runs, and the number of times a food source is found, and foraging occurs in these runs varies and depends on the number of scouts in the swarm. In these simulation runs, the number of runs where complete forage occurs with respect to the number of runs where foraging occurs derives this percentage result.

The results are also used to create a table that can inform on the speed and optimality of both foraging behaviours by comparing their times of complete forage and the energy exerted (which are number of times pheromones are reinforced), given either single or double food sources. This is presented in the analysis section ahead.

4.1.1. Open World Results

Each experiment has been run for 100 times in 5 minutes duration, and the graphs presented shows the results for the each of the 100 runs that make up the experiments (1-12) run in an open spaced world with no obstacles.

4.1.1.1. General Results

In the tables [see appendix 8.1] some results are taken while considering "successful forage only" because it has been observed that even though a food source is found, and pheromone created and reinforced, there is no food foraged. This can be due to several scenarios that might arise during the foraging process like: - (i) failure of flocks to work together due to too different opinions, (ii) decay of a part of pheromone trail below certain threshold that cannot be reinforced again, and continuous reinforcement of good part but not being able to return to the nest since the trail has been cut off etc. Other likely scenarios are discussed in chapter 5. Due to this phenomenon, when it occurs in an experiment, the "successful forage only" results remove the results arising from them to present the average result. Although, all scenarios are accounted for in the other presented results in the tables. The graphs show the results where all scenarios are accounted for. On the x-axis is the number of foods foraged, and on the y-axis is the number of times the pheromone trail(s) was reinforced (work exerted).

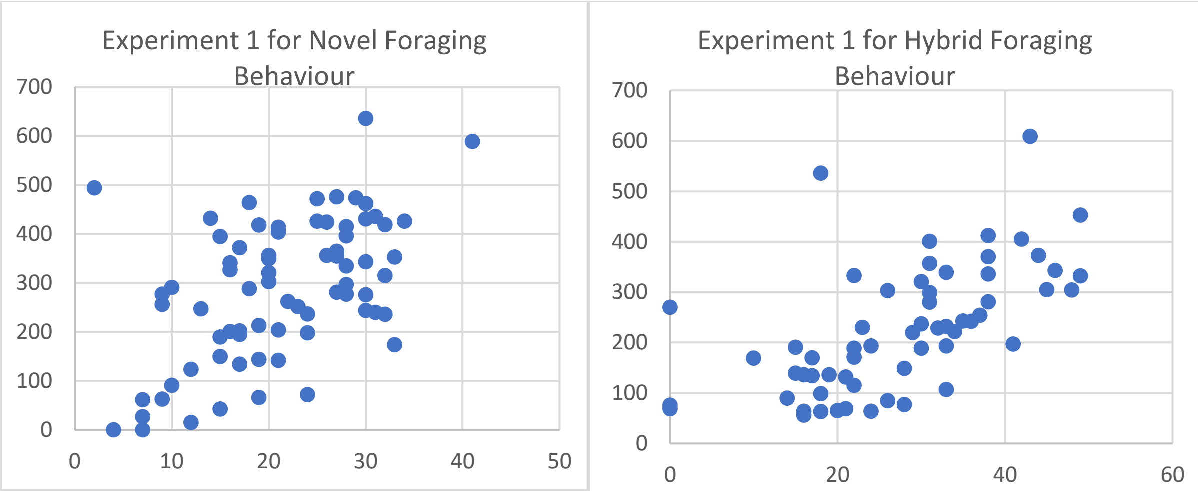


Figure 18. *Open World – Experiment 1: Number of foraged foods vs. Number of times pheromones are reinforced.*

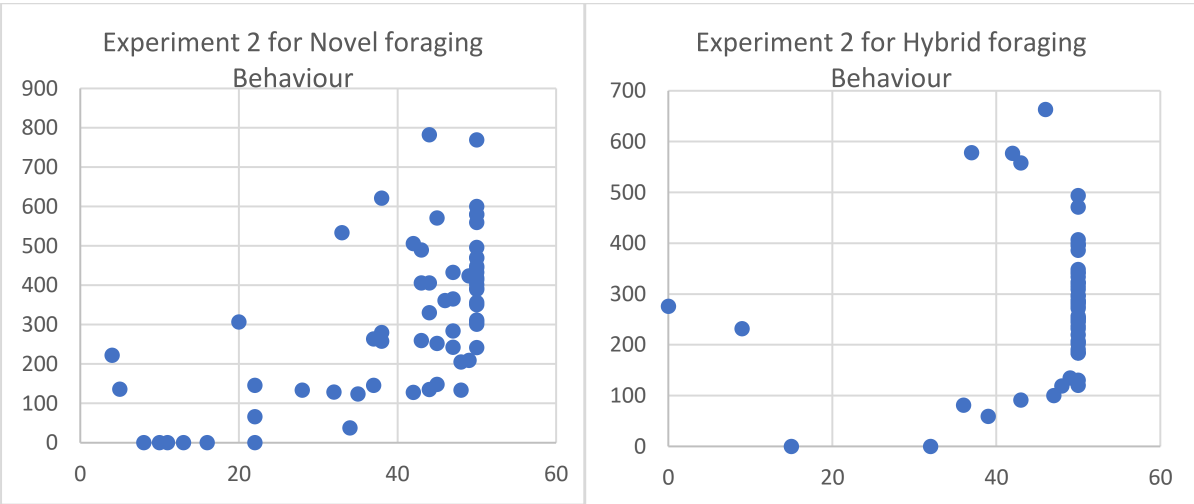


Figure 19. *Open World – Experiment 2: Number of foraged foods vs. Number of times pheromones are reinforced.*

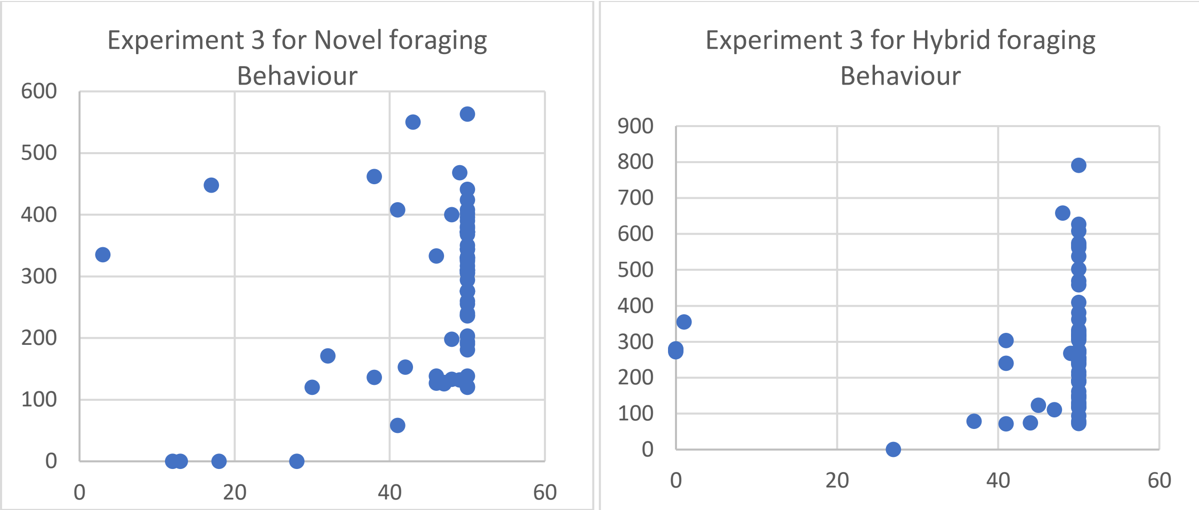


Figure 20. *Open World – Experiment 3: Number of foraged foods vs. Number of times pheromones are reinforced.*

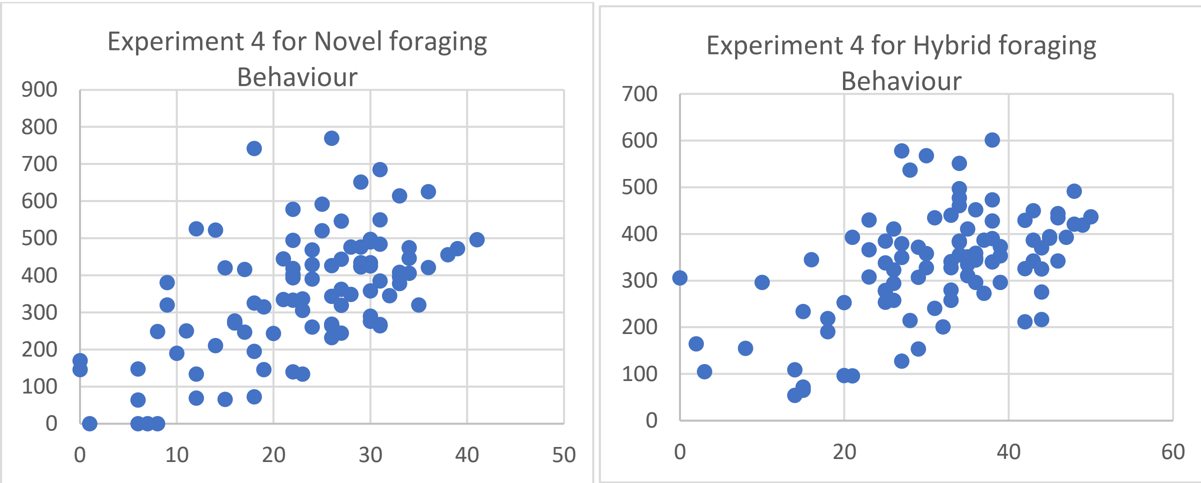


Figure 21. *Open World – Experiment 4: Number of foraged foods vs. Number of times pheromones are reinforced.*

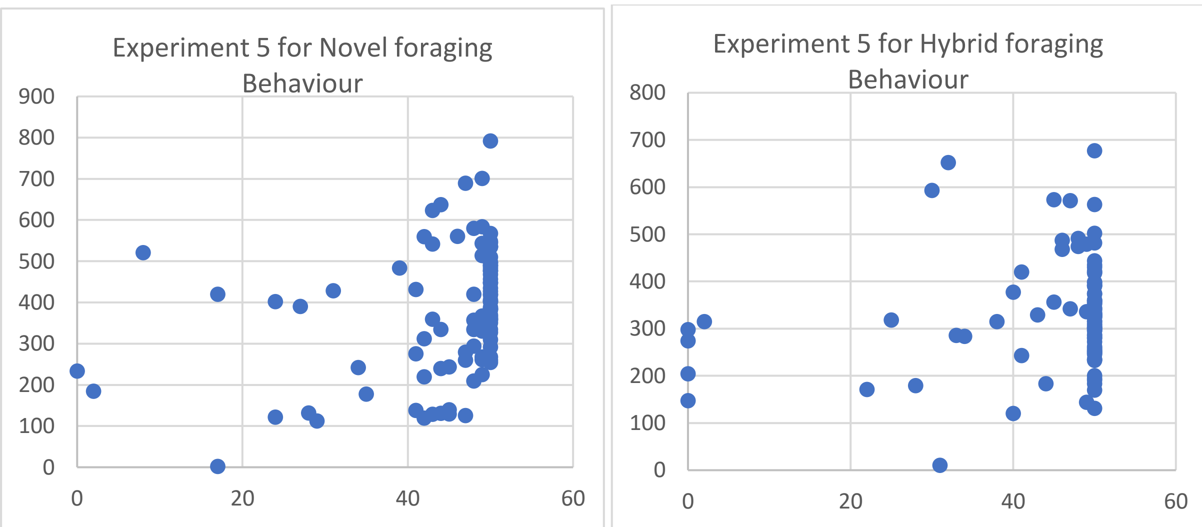


Figure 22. *Open World – Experiment 5: Number of foraged foods vs. Number of times pheromones are reinforced.*

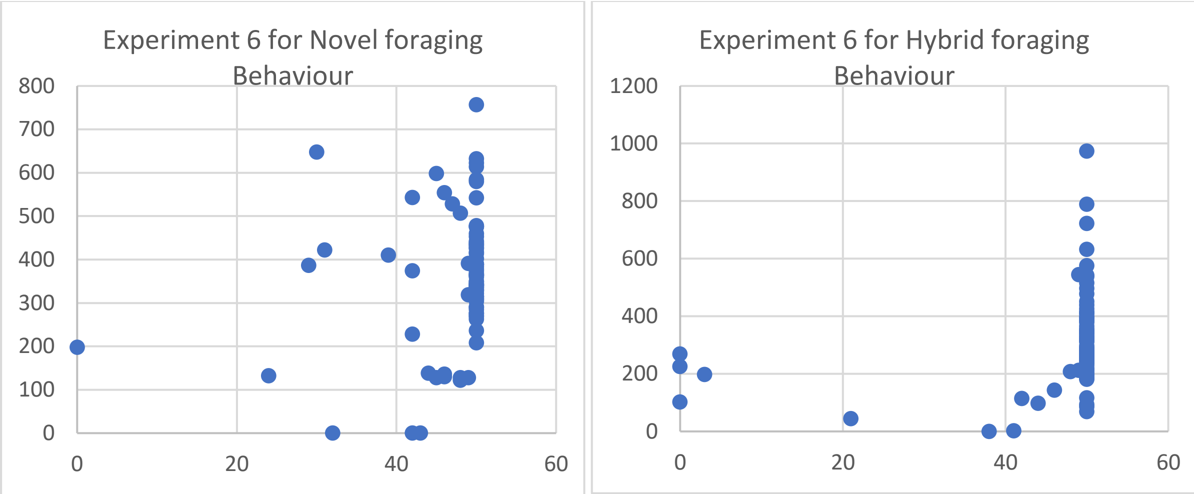


Figure 23. *Open World – Experiment 6: Number of foraged foods vs. Number of times pheromones are reinforced.*

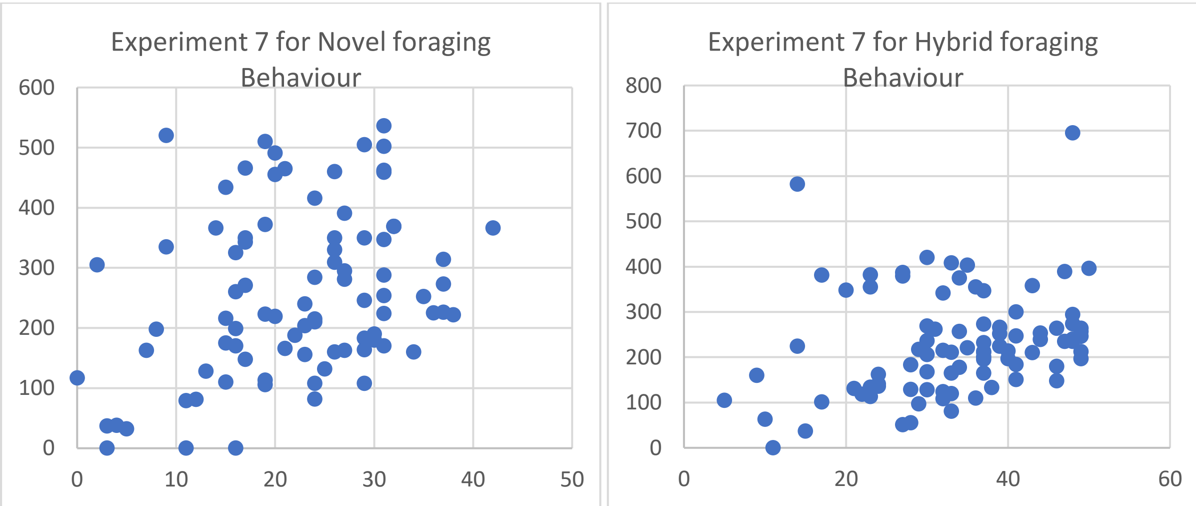


Figure 24. *Open World – Experiment 7: Number of foraged foods vs. Number of times pheromones are reinforced.*

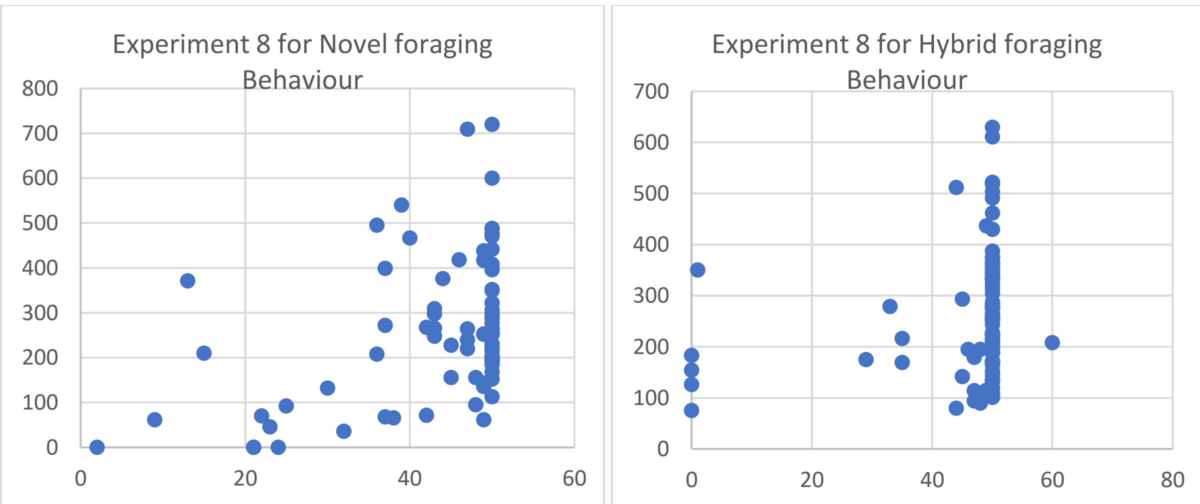


Figure 25. *Open World – Experiment 8: Number of foraged foods vs. Number of times pheromones are reinforced.*

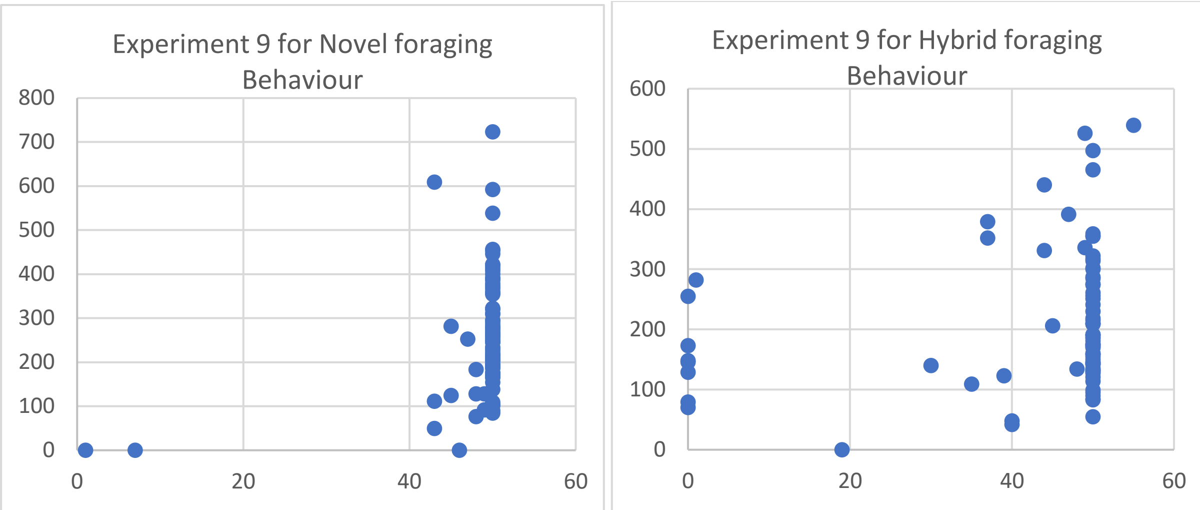


Figure 26. *Open World – Experiment 9: Number of foraged foods vs. Number of times pheromones are reinforced.*

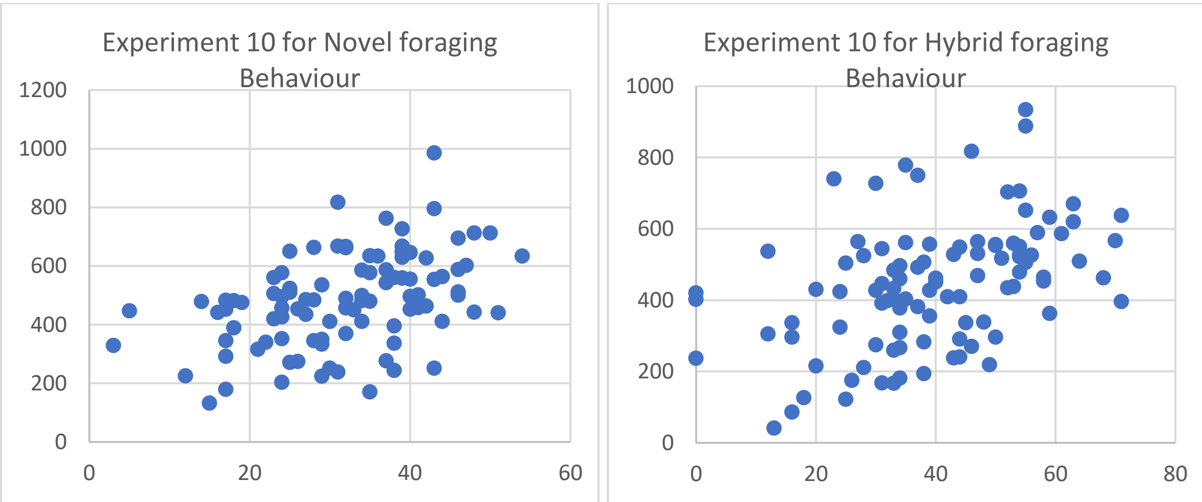


Figure 27. *Open World – Experiment 10: Number of foraged foods vs. Number of times pheromones are reinforced.*

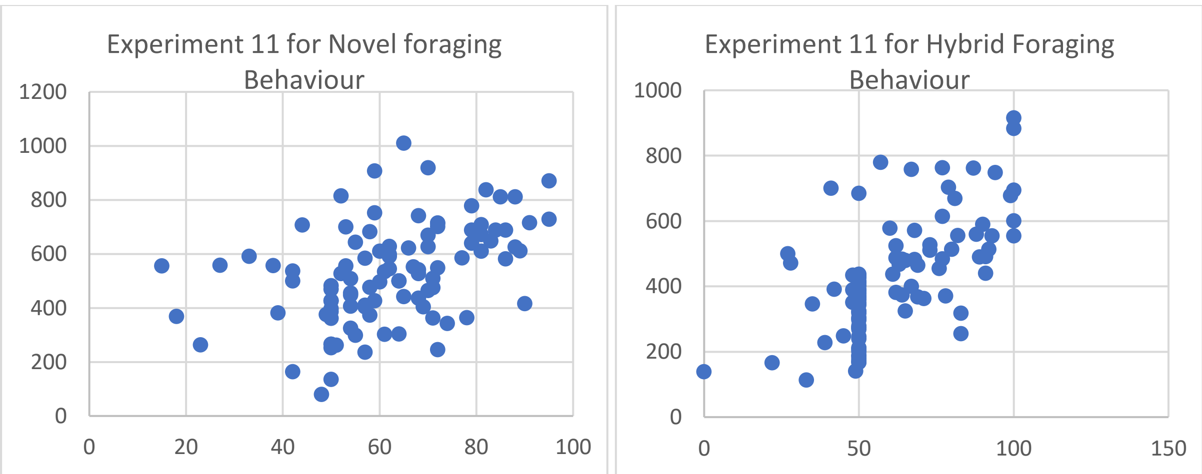


Figure 28. *Open World – Experiment 11: Number of foraged foods vs. Number of times pheromones are reinforced.*

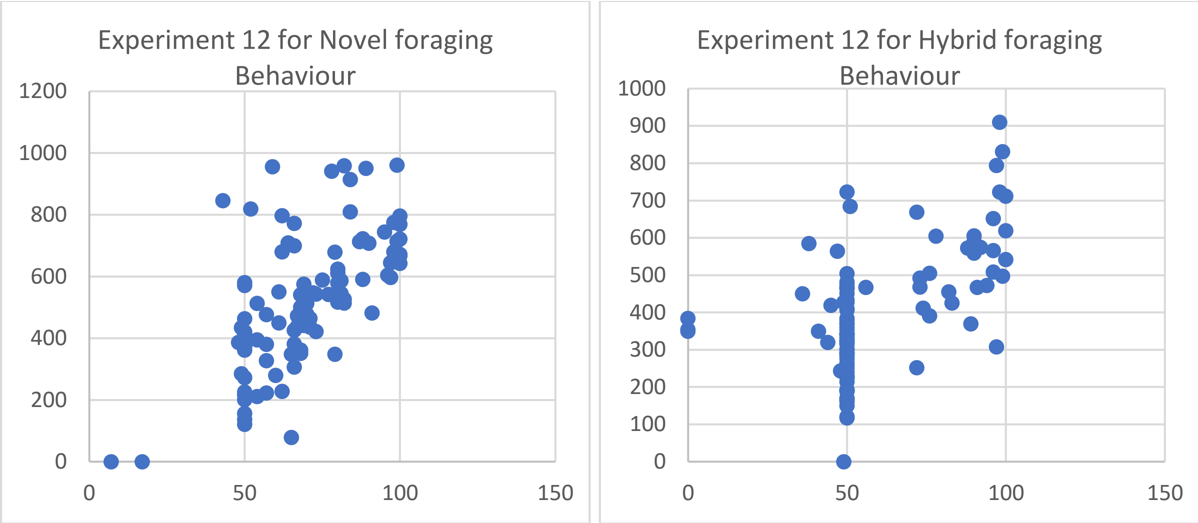


Figure 29. *Open World – Experiment 12: Number of foraged foods vs. Number of times pheromones are reinforced.*

4.1.1.2. Complete Forage Results

Any of the 100 runs in each experiment where complete forage occurred is represented in the graphs presented below. This graphs present results which shows how fast a food source was completely foraged, and the number of times pheromone reinforcement occurred during the foraging task in a run. [to see tables, please see Appendix 8.1]. The trendline of each graph are also shown. On the x-axis is the time taken to completely forage from a food source, and on the y-axis, is the number of times the pheromone trail was reinforced.

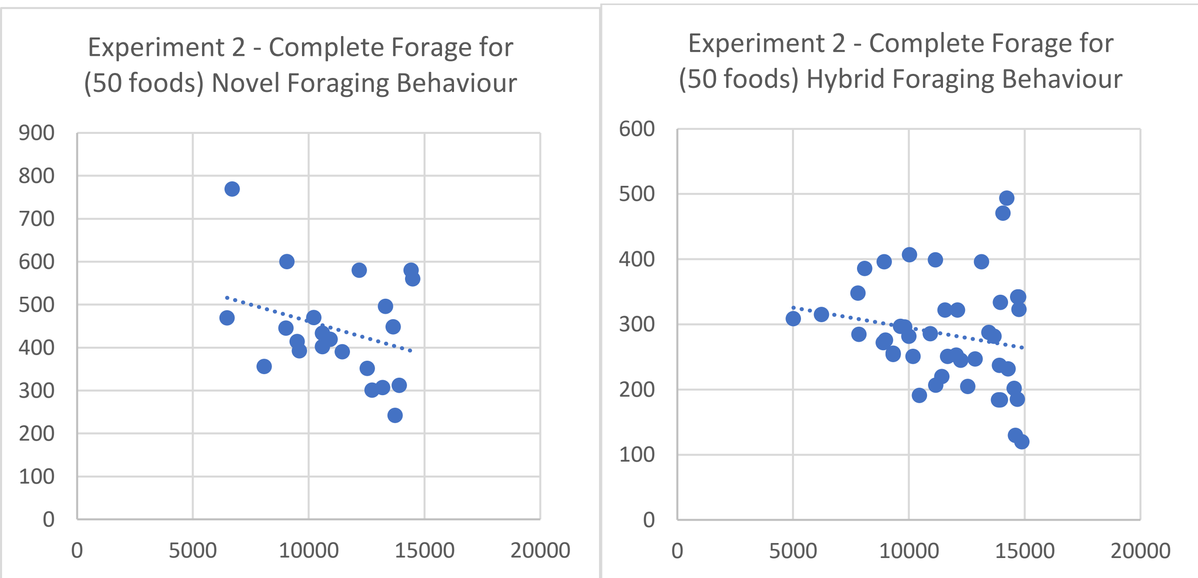
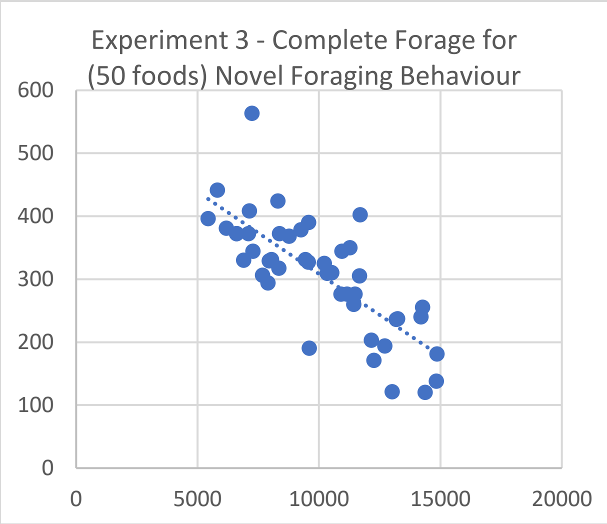


Figure 30. *Open World – Experiment 2 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*



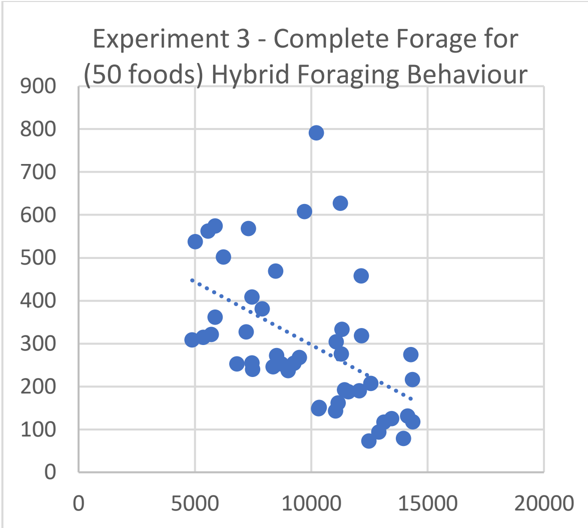


Figure 31. *Open World – Experiment 3 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

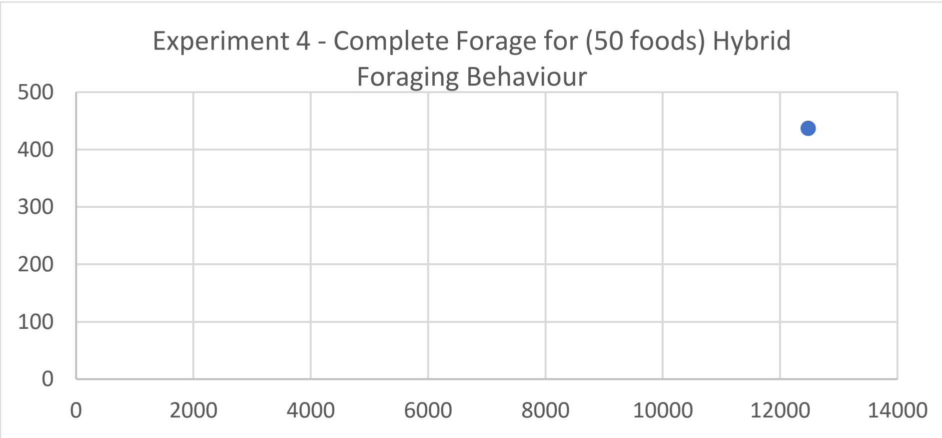
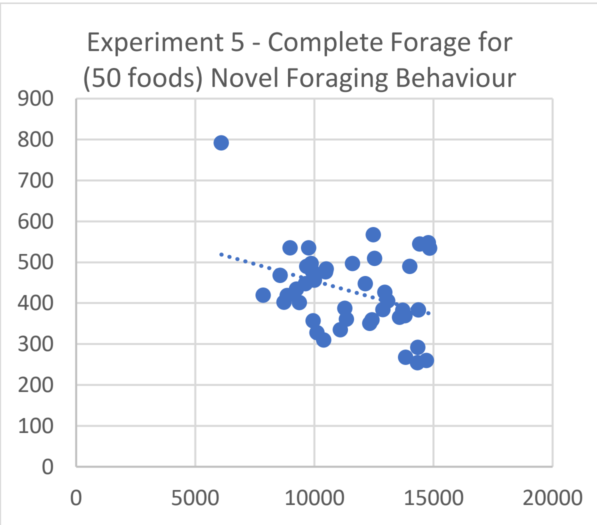


Figure 32. *Open World – Experiment 4 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*



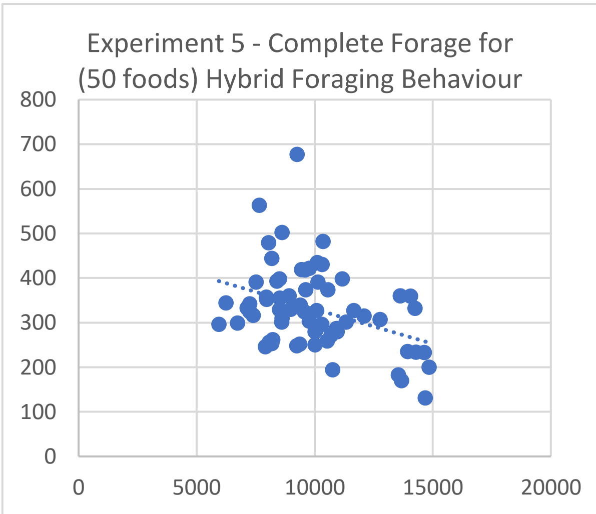
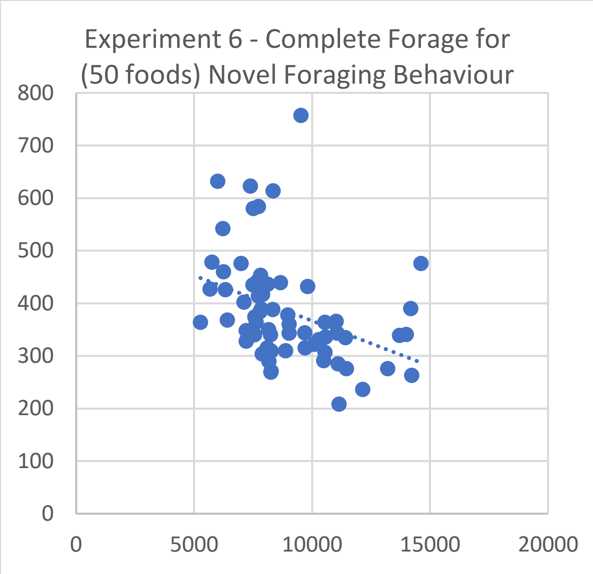


Figure 33. *Open World – Experiment 5 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*



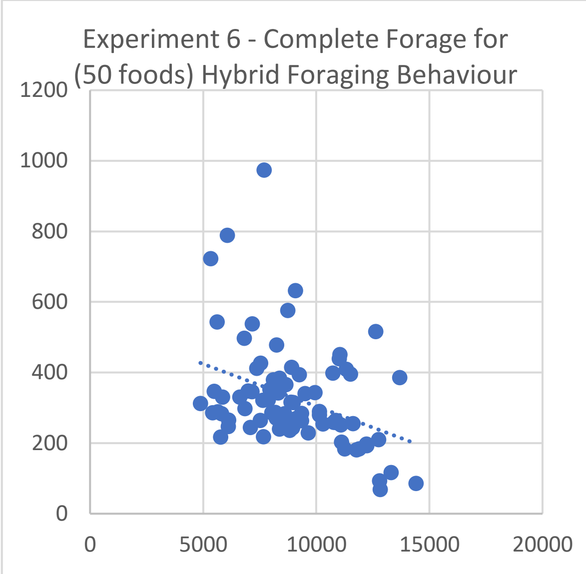


Figure 34. *Open World – Experiment 6 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

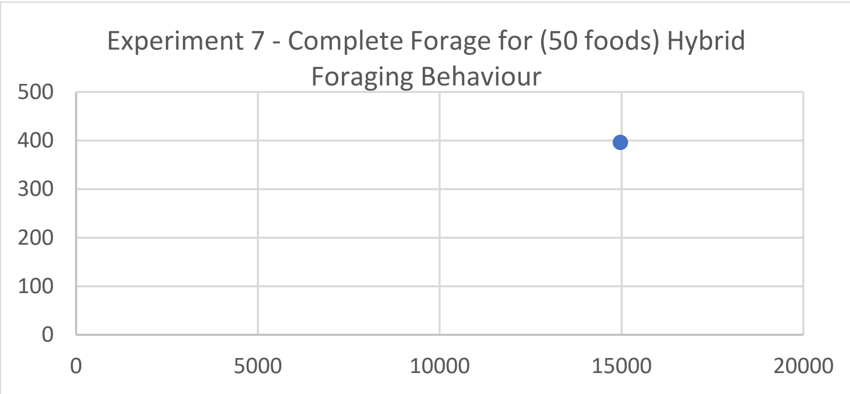
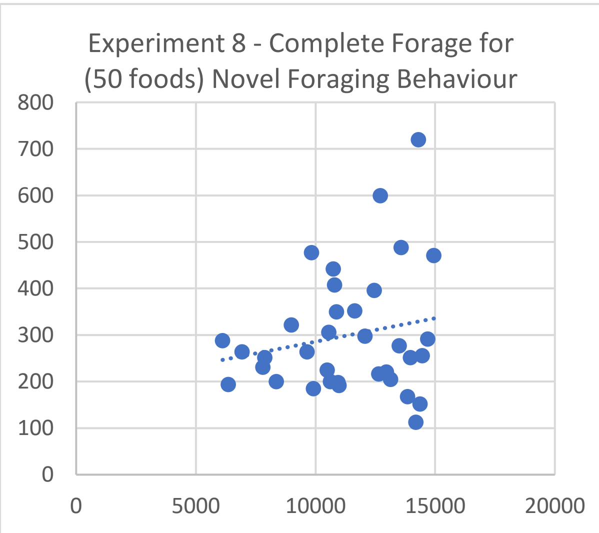


Figure 35. *Open World – Experiment 7 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*



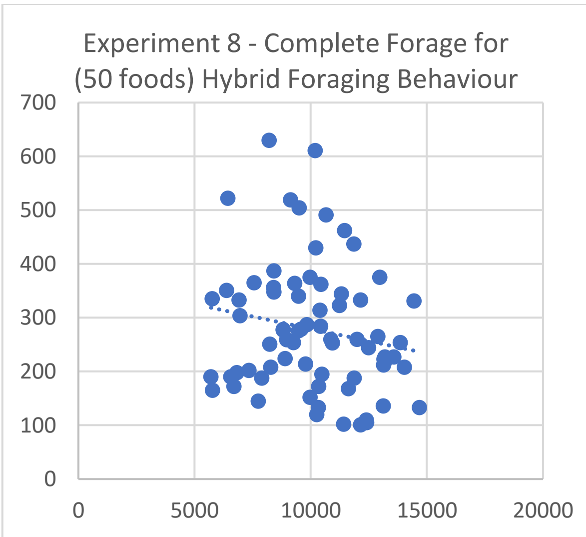


Figure 36. *Open World – Experiment 8 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

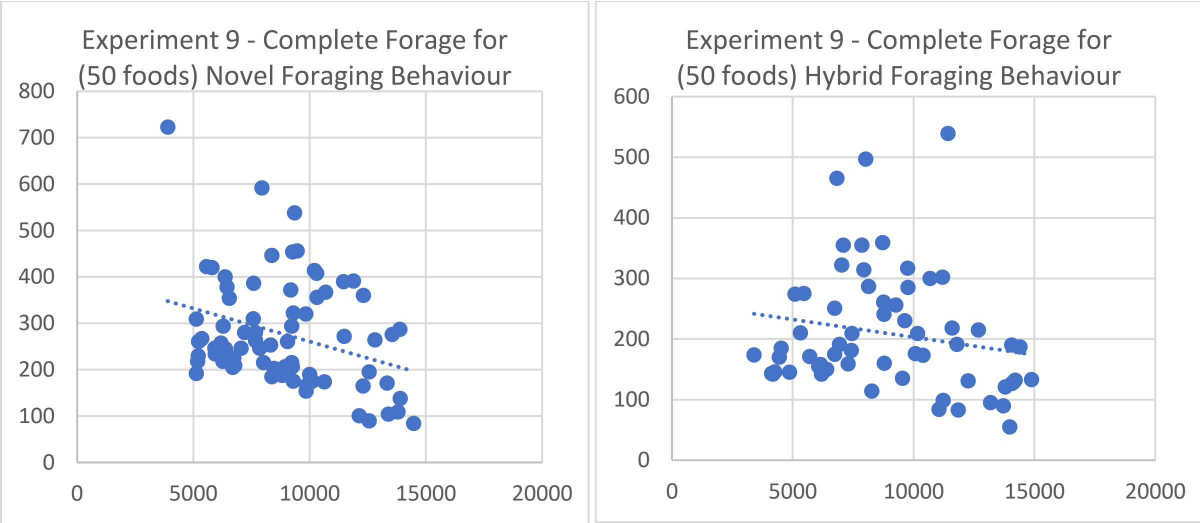


Figure 37. *Open World – Experiment 9 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

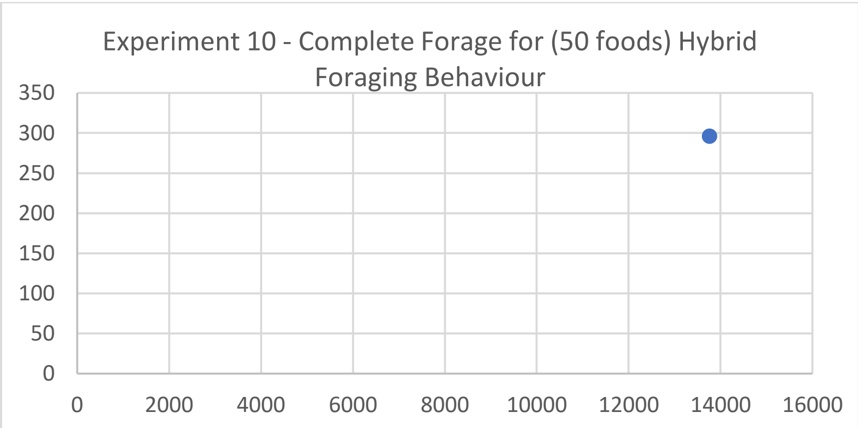


Figure 38. *Open World – Experiment 10 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

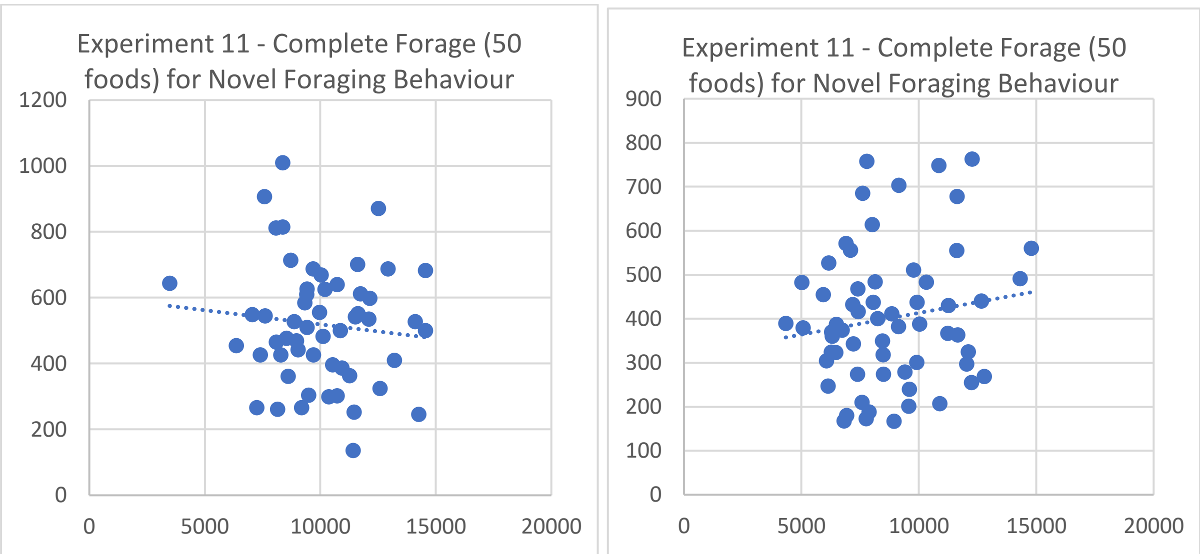


Figure 39. *Open World – Experiment 11 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

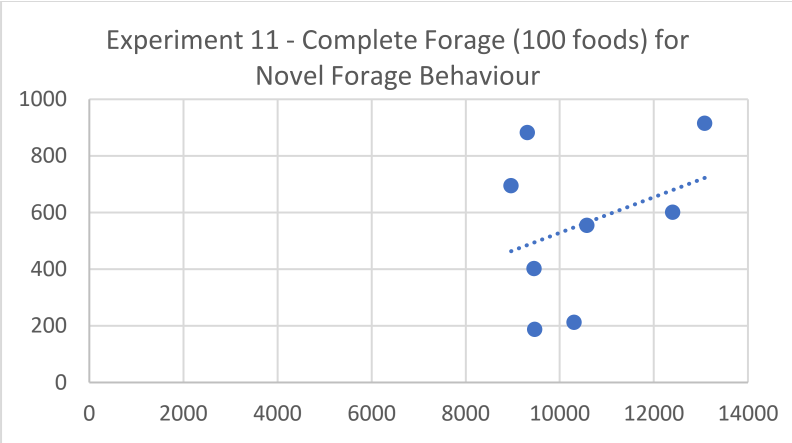


Figure 40. *Open World – Experiment 11 Complete Forage (100 foods): Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

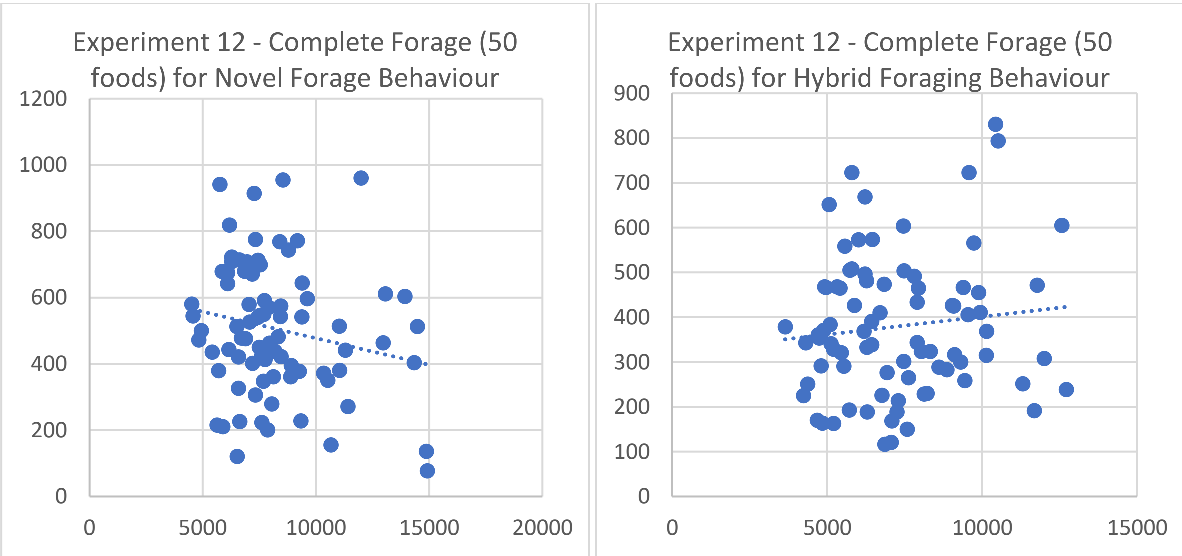


Figure 41. *Open World – Experiment 12 Complete Forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

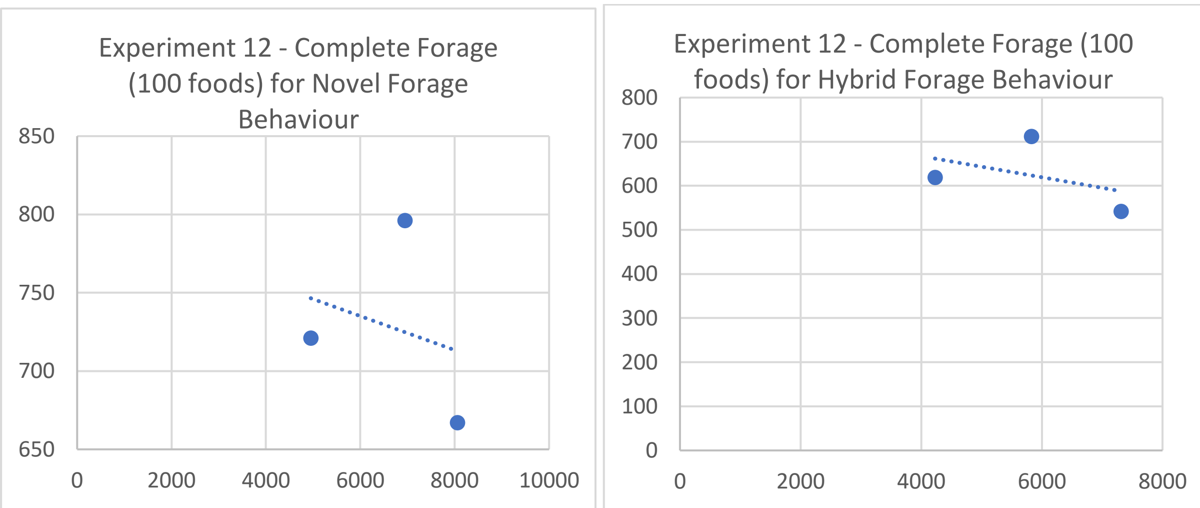


Figure 42. *Open World – Experiment 12 Complete Forage (100 foods): Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

4.1.2. **Obstacle World Results**

This section presents the results of the experiments, which were done in a world filled with obstacles, with different instances like: swarm size and composition, and number of food sources. The experiments are conducted with the Novel and Hybrid foraging behaviour to also take into account the uncertainties, and hindrances that can deter the completion of the foraging task. The results are divided into two types: (a) General results – which presents the results of how much food is foraged in comparison to the amount of work exerted. (b)Complete forage results – present results where a food source is foraged from till its exhausted, therefore presenting the time taken to completely forage from the food source in comparison to the amount of work exerted.

4.1.2.1. General Results

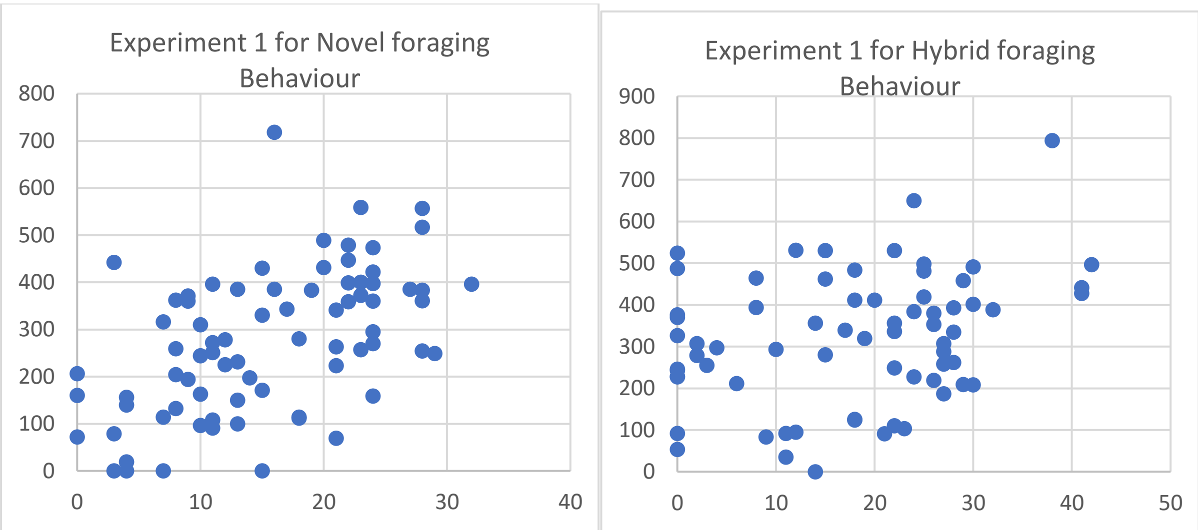


Figure 43. *Obstacle World - Experiment 1: Number of foraged foods vs. Number of times pheromones are reinforced.*

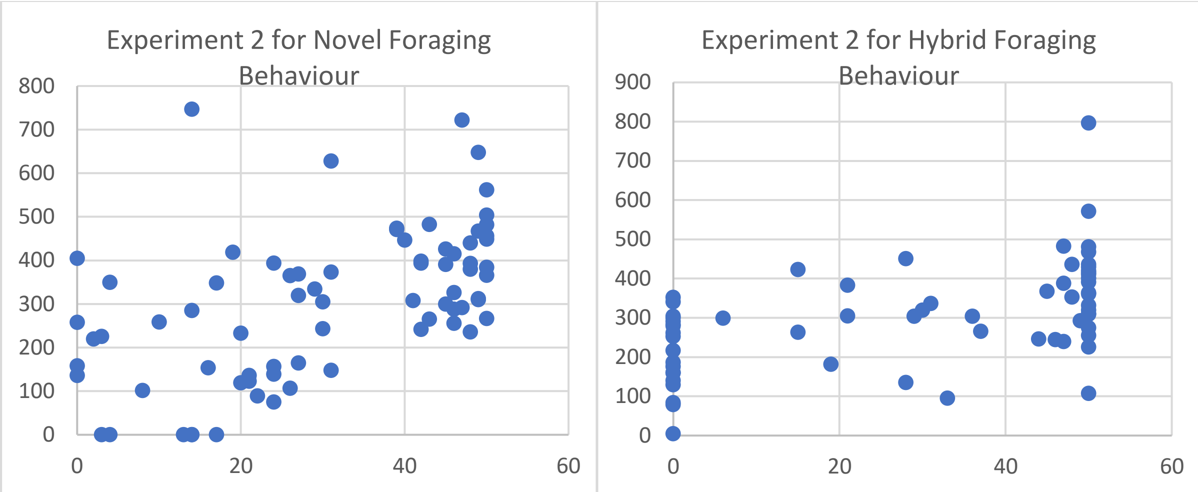


Figure 44. *Obstacle World - Experiment 2: Number of foraged foods vs. Number of times pheromones are reinforced.*

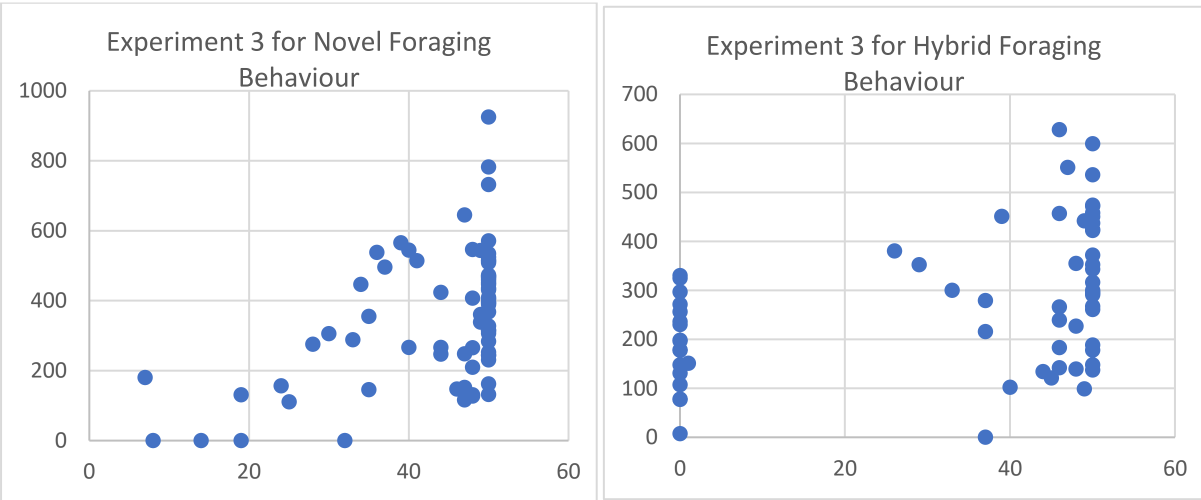


Figure 45. *Obstacle World - Experiment 3: Number of foraged foods vs. Number of times pheromones are reinforced.*

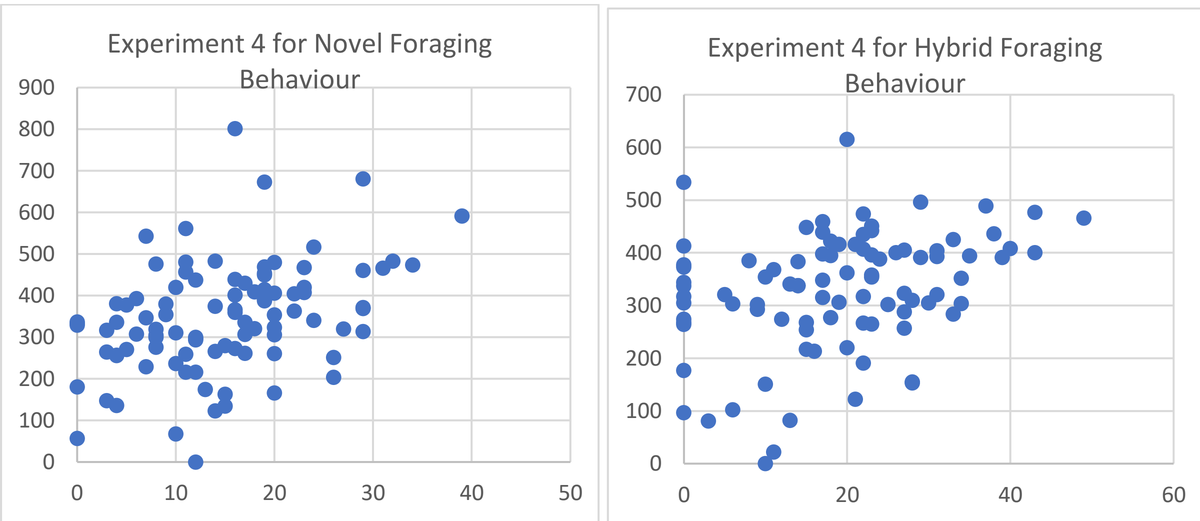


Figure 46. *Obstacle World - Experiment 4: Number of foraged foods vs. Number of times pheromones are reinforced.*

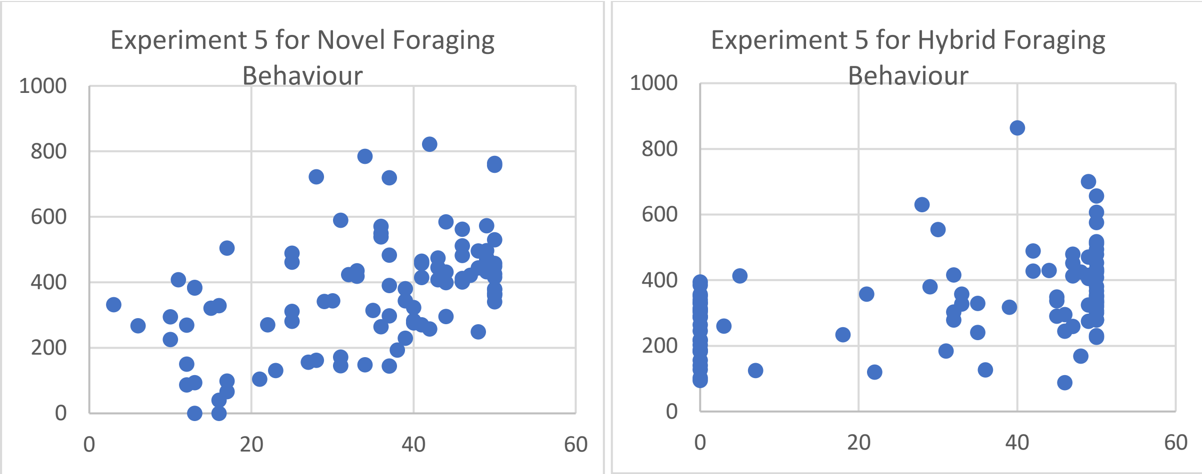


Figure 47. *Obstacle World - Experiment 5: Number of foraged foods vs. Number of times pheromones are reinforced.*

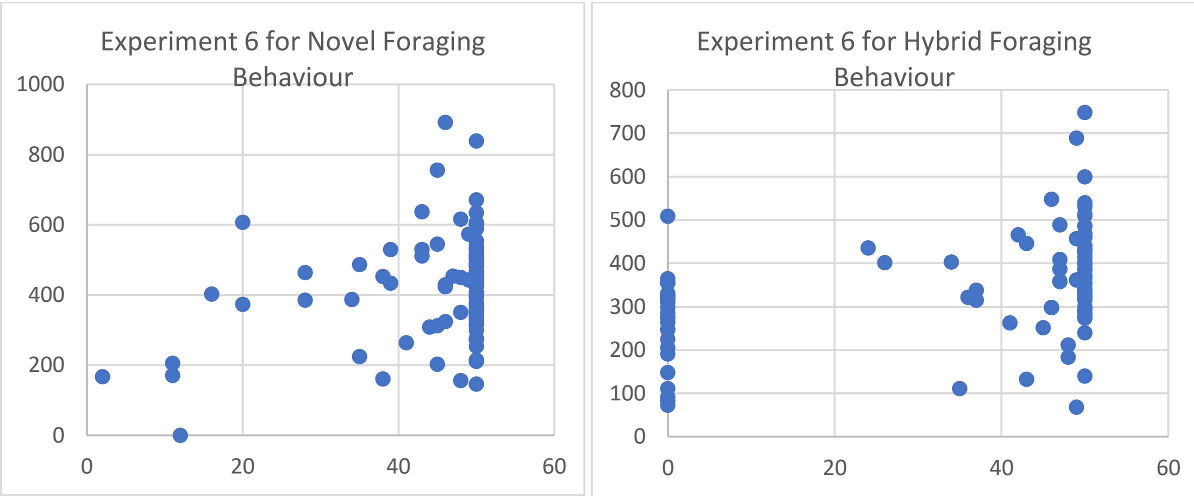


Figure 48. *Obstacle World - Experiment 6: Number of foraged foods vs. Number of times pheromones are reinforced.*

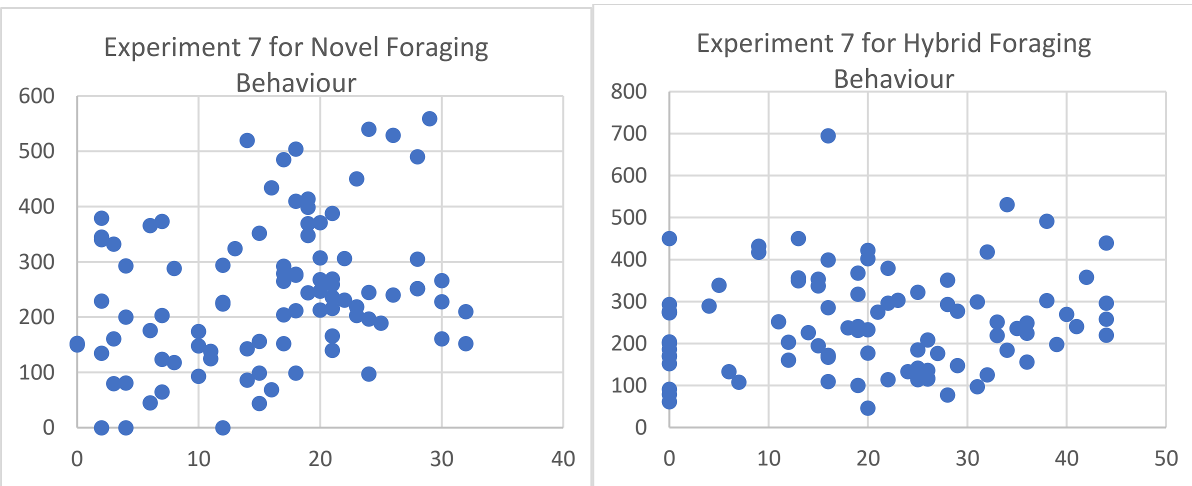


Figure 49. *Obstacle World - Experiment 7: Number of foraged foods vs. Number of times pheromones are reinforced.*

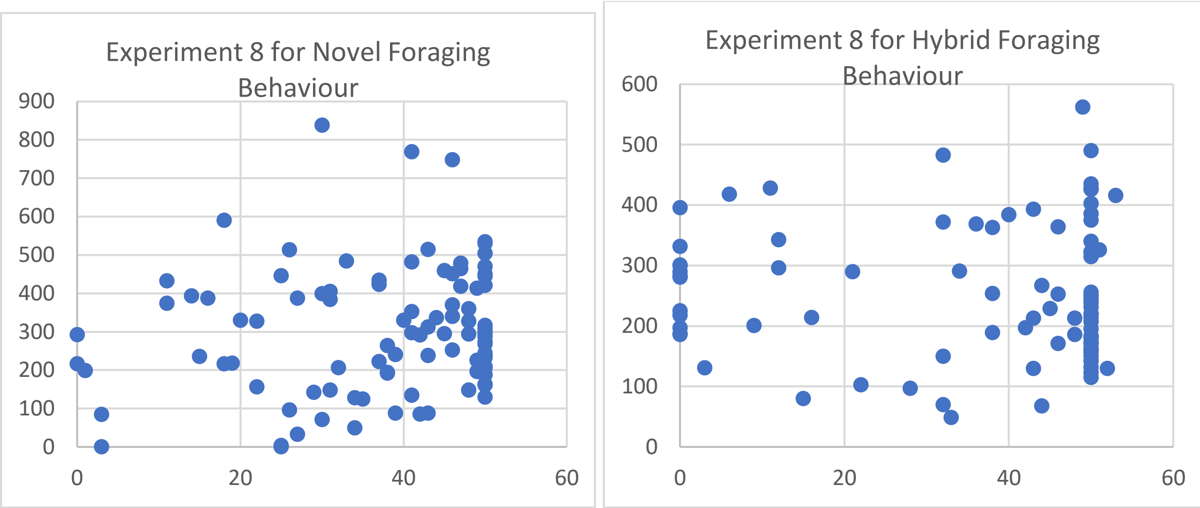


Figure 50. *Obstacle World - Experiment 8: Number of foraged foods vs. Number of times pheromones are reinforced.*

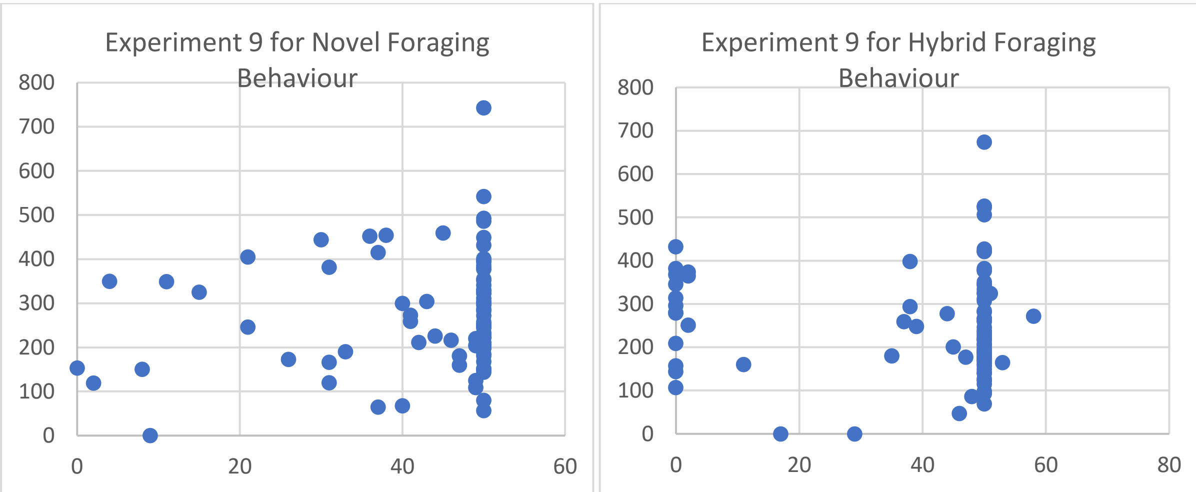


Figure 51. *Obstacle World - Experiment 9: Number of foraged foods vs. Number of times pheromones are reinforced.*

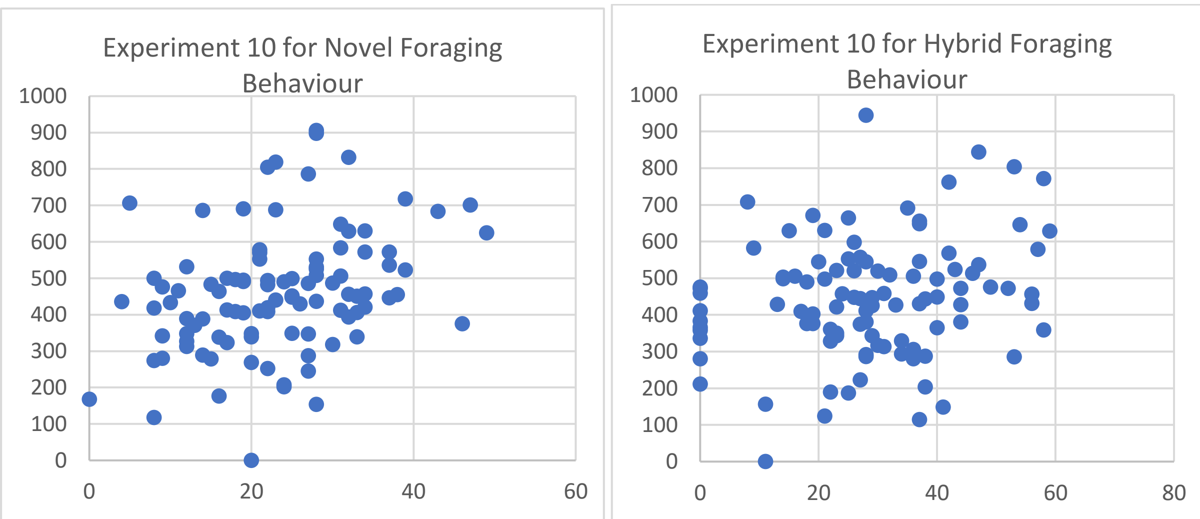


Figure 52. *Obstacle World - Experiment 10: Number of foraged foods vs. Number of times pheromones are reinforced.*

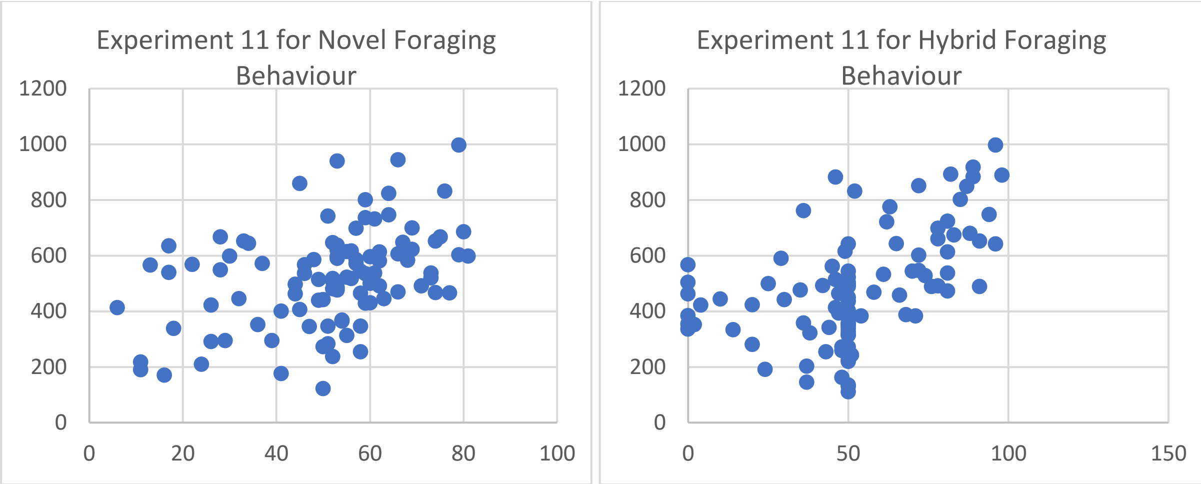


Figure 53. *Obstacle World - Experiment 11: Number of foraged foods vs. Number of times pheromones are reinforced.*

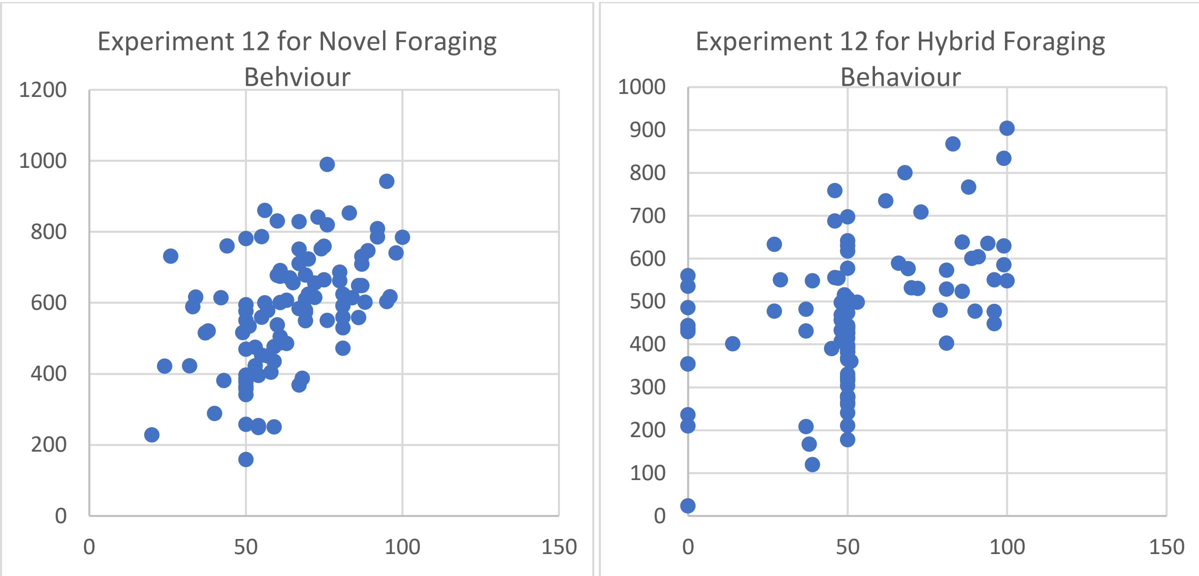


Figure 54. *Obstacle World Experiment 12: Number of foraged foods vs. Number of times pheromones are reinforced.*

4.1.2.2. Complete Forage Results

The results of experiments in which complete forage occurred in the simulation runs. The simulation runs are done in an obstacle filled world. These experiments would account for environmental interferences that can stop foraging processes. This can create extreme situations, where the performance of both foraging behaviours would properly reveal its weaknesses and strengths. On the x-axis is the time taken to completely forage from a food source, and on the y-axis, is the number of times the pheromone trail was reinforced.

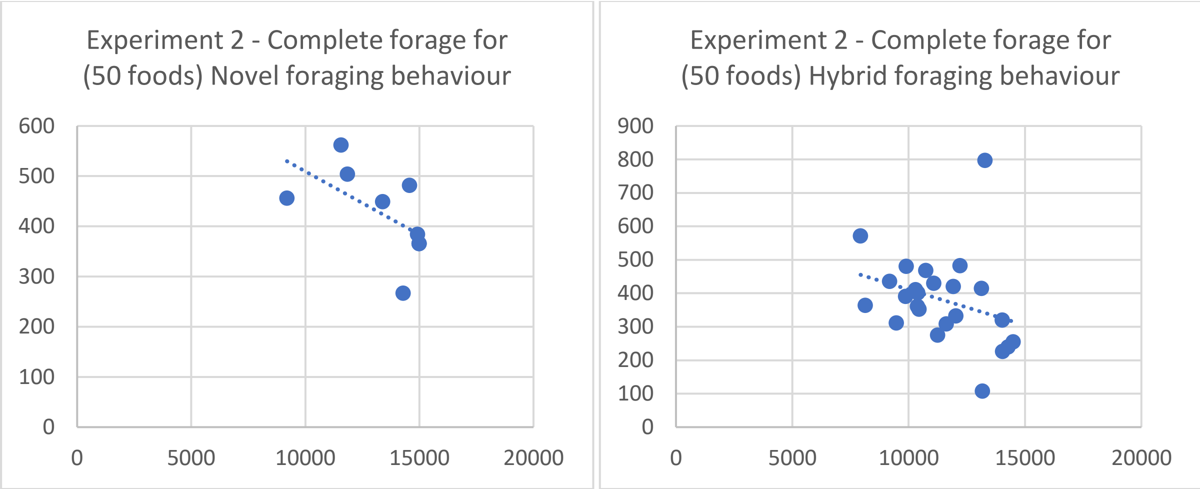


Figure 55. *Obstacle World – Experiment 2 Complete forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

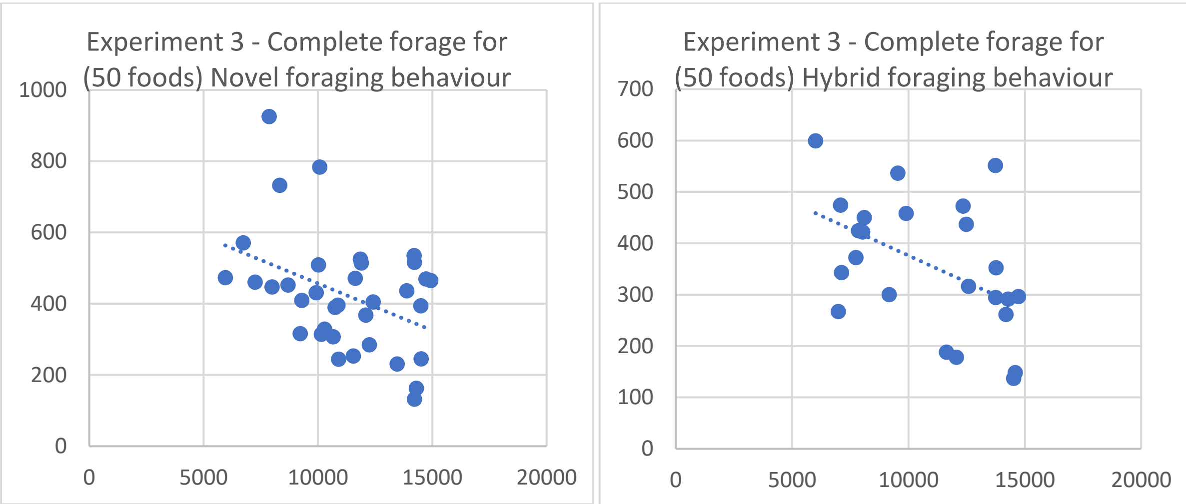


Figure 56. *Obstacle World – Experiment 3 Complete forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

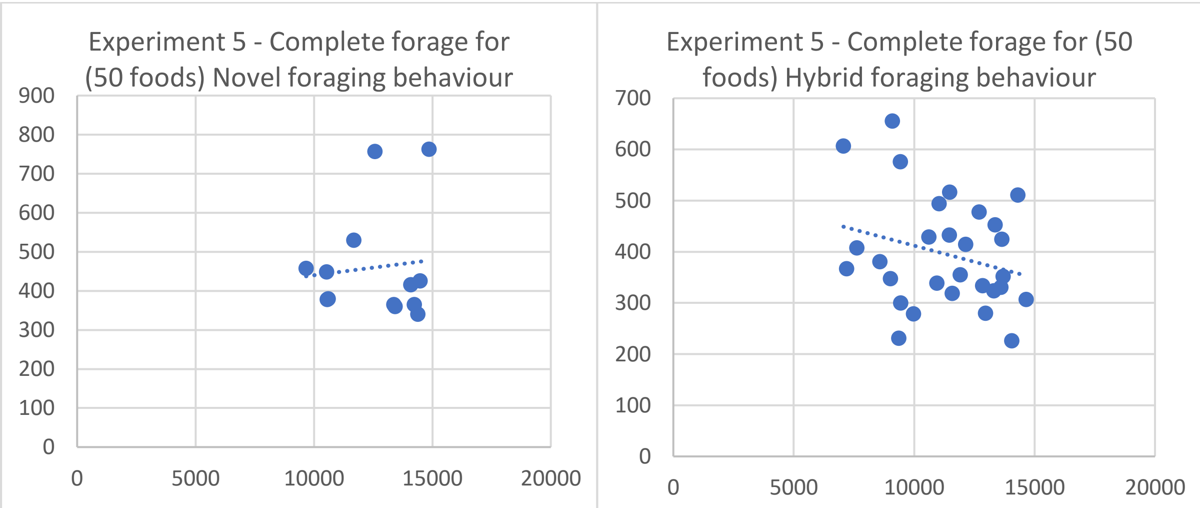


Figure 57. *Obstacle World – Experiment 5 Complete forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

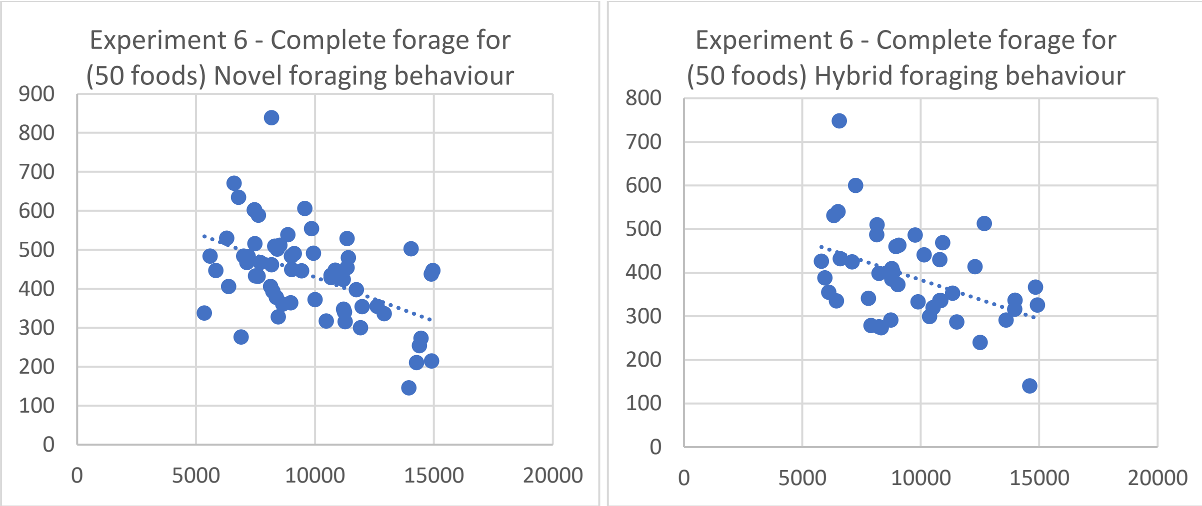


Figure 58. *Obstacle World – Experiment 6 Complete forage: Time taken to completely forage food source vs. Number of times pheromones are reinforced.*

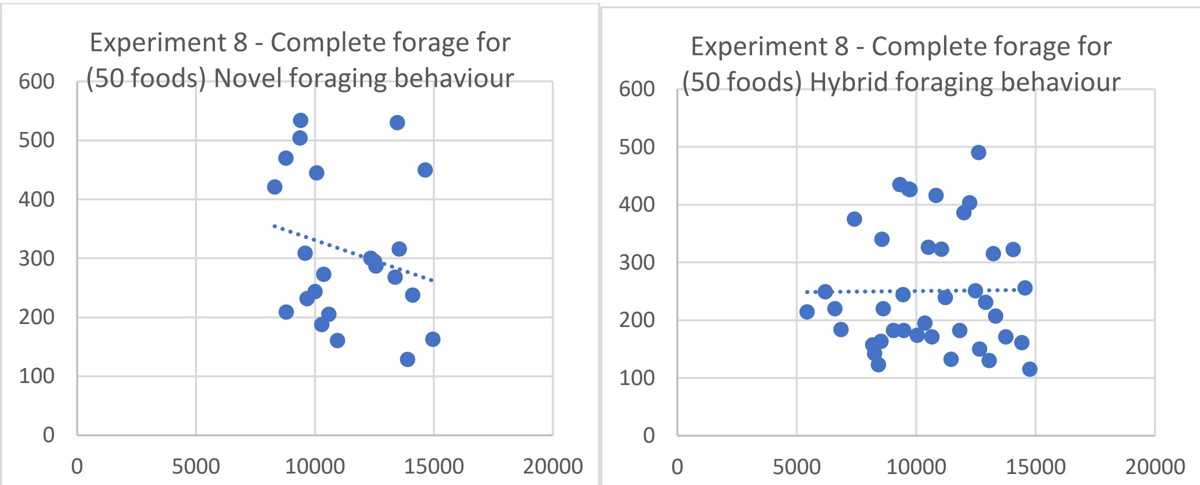


Figure 59. *Obstacle World – Experiment 8 Complete forage: Time taken to completely forage from a food source vs. Number of times pheromones are reinforced.*

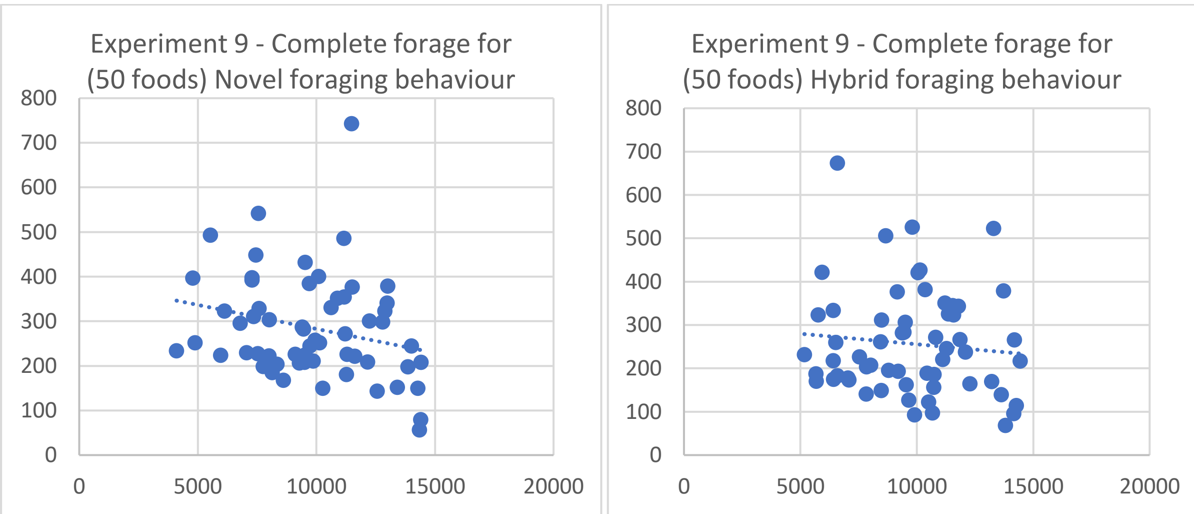


Figure 60. *Obstacle World – Experiment 9 Complete forage: Time taken to completely forage from a food source vs. Number of times pheromones are reinforced.*

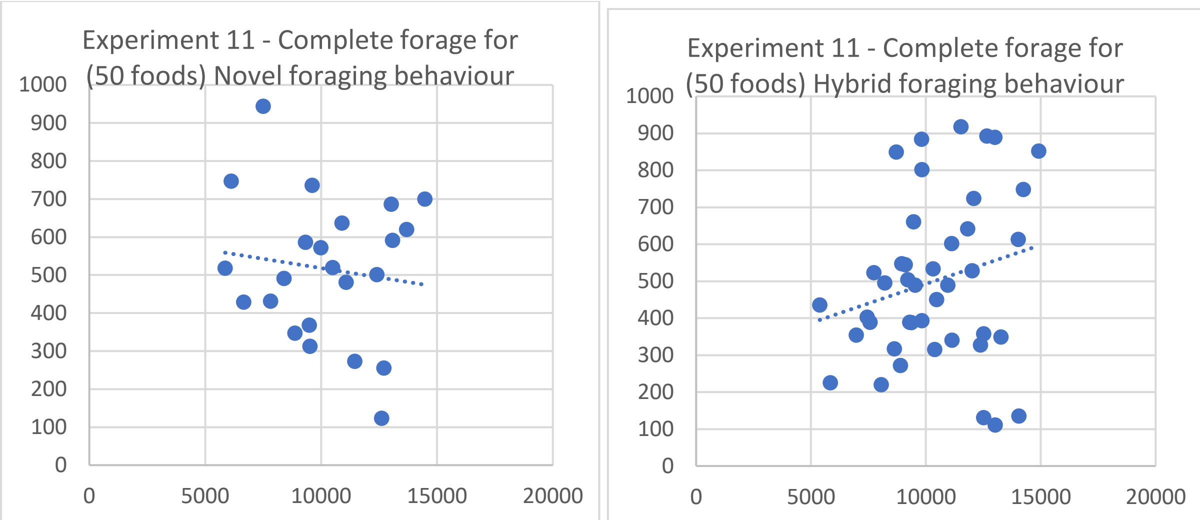


Figure 61. *Obstacle World – Experiment 11 Complete forage: Time taken to completely forage from a food source vs. Number of times pheromones are reinforced.*

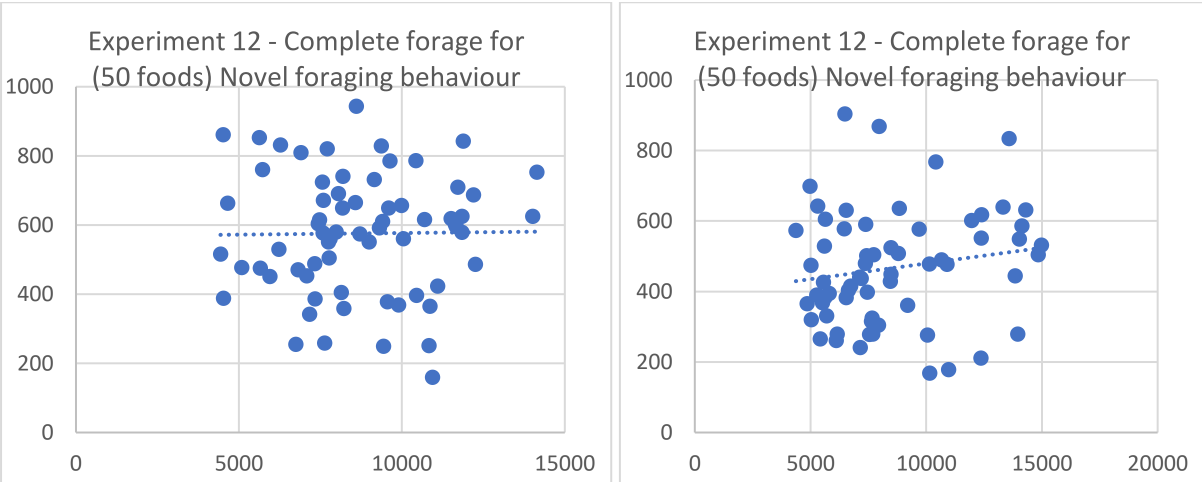


Figure 62. *Obstacle World – Experiment 12 Complete forage: Time taken to completely forage from a food source vs. Number of times pheromones are reinforced.*

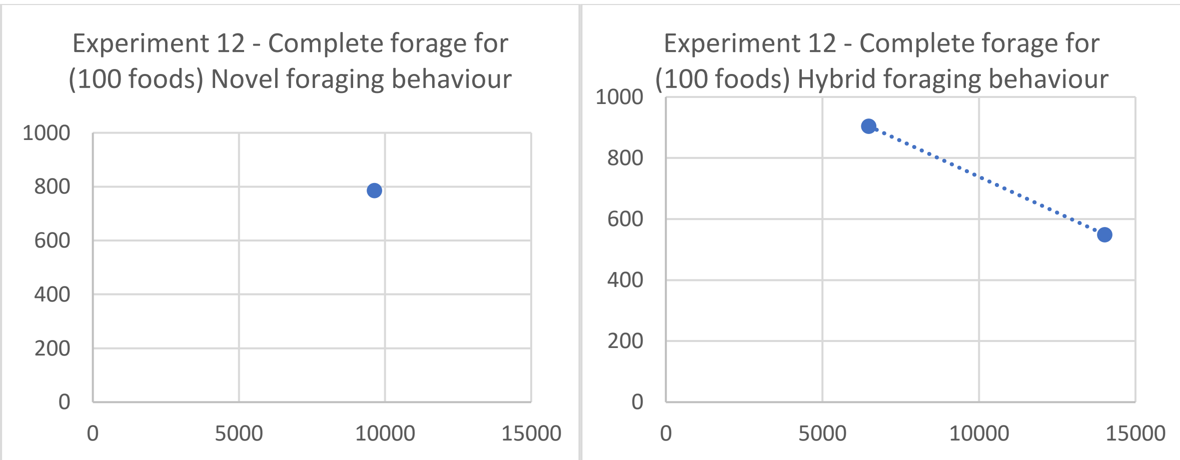


Figure 63. *Obstacle World – Experiment 12 Complete forage (100): Time taken to completely forage from a food source vs. Number of times pheromones are reinforced.*

4.2. ANALYSIS

This section presents analysis of the results according to the experiments conducted. A conclusive analysis is given from the results, where the research questions are correlated with the experiments, and the answers are inferred from the results.

4.2.1. Experimental Analysis

The analysis of the results of each experiment is given in this section.

4.2.1.1. Experiment 1 Analysis

This experiment was conducted for – a single scout, ten followers and a single food source.

- Open World Experiment: - In the given time-span, foraging with the hybrid foraging behaviour was able to gather more food than the novel foraging behaviour while exerting lesser work, despite several unsuccessful foraging attempts. The food source was never exhausted, and this can be due to the fact that the swarm members were few. The Hybrid behaviour proves to be optimal and performs better than the novel foraging behaviour. Although, as seen in the results, foraging with the hybrid behaviour can result to some unsuccessful foraging attempts, due to the decay of the pheromone trail which can cut off the food source from the nest, especially the pheromones laid earlier and closer to the food source, which are more likely to decay below threshold. While waiting and forming a flock, time elapses and the trail decays, by the time the flock is formed, some part of the trail might have decayed below threshold for reinforcement. Hence, making the foragers to loop back and forth along the pheromone trail until the simulation run has finished. This scenario is discussed in chapter 5.

- Obstacle World Experiment: - In the given time-span, foraging with the hybrid foraging behaviour was able to gather more food than the novel foraging behaviour but exerting more work. Foraging with both behaviours showed some unsuccessful foraging attempts, and this can be as a result of the obstacles, hence, presenting a more difficult pheromone trail to travel along. In the hybrid foraging behaviour this can result to many flock members leaving the flock because none of their recognised flock mates is within the pheromone trail. In the novel foraging behaviour, this can result to agents returning home after failing to travel successfully along the pheromone. The scenario of early pheromone trail decay, which occurs when the trail is not reinforced for a while after its created, can also affect this experiment, because once a pheromone trail is not traversable, it cannot be reinforced, and therefore it decays below threshold. This would cut off the nest from the food source.

4.2.1.2. Experiment 2 Analysis

This experiment was conducted for – a single scout, thirty followers and a single food source.

- Open World Experiment: foraging with the hybrid behaviour was able to forage more food than the novel behaviour while exerting lesser work, despite several unsuccessful foraging attempts. Early pheromone trail decay below threshold as explained in the previous analysis can lead to these unsuccessful foraging attempts. The food source was exhausted (complete forage) with both the novel and hybrid behaviour. The work exerted to completely forage using the hybrid behaviour was about half of the work exerted using the novel behaviour. Given that the food source was found, and foraging occurs, using the hybrid foraging behaviour, complete forage occurred for 76% of all attempts, while using the novel foraging behaviour, complete forage occurred for 34% of all attempts. The time taken for complete forage using the hybrid behaviour was slightly higher than the time taken when using the novel behaviour. The hybrid behaviour proved to be more optimal, consistent and better than the novel behaviour, but not faster in this experiment

- Obstacle World Experiment: while considering both successful and unsuccessful foraging attempts, foraging with the novel behaviour was able to forage more food than the hybrid behaviour, while exerting lesser work. Considering only successful foraging attempts, the hybrid foraging behaviour was able to forage more food than the novel foraging behaviour, while exerting more work. These results show that with obstacles, foraging with the hybrid behaviour can lead to more unsuccessful foraging attempts than the novel behaviour. This can be due to the fact that as swarm size increase, opinions in a flock increase and the flock can easily disperse when the pheromone trail is difficult to travel, due to an agent not finding any of its flock members within the pheromone trail. Since the pheromone trail is hard to traverse, some parts do not get much reinforcement, and then results to the food source getting cut off from the pheromone trail, and as a result there is continuous looping and reinforcement along the remaining parts of the pheromone trail. This also occurs in novel foraging behaviour. Given that the food source is found, and foraging occurs, the hybrid foraging behaviour resulted to complete forage occurring 38% of the times and faster than the case of novel foraging behaviour, where complete forage occurred 12% of the times. The hybrid behaviour proved to be faster and more optimal than the novel behaviour when exhaustively foraging from a food source but less consistent in general. The novel foraging behaviour proved to gather more food when all possibilities are considered (consistent) and with less work than the hybrid behaviour.

4.2.1.3. Experiment 3 Analysis

This experiment was conducted for – a single scout, fifty followers, and a single food source.

- Open World Experiment: considering both successful and unsuccessful foraging attempts, foraging with both the novel and hybrid behaviour gathered roughly the same amount of food, but the novel behaviour did so with less work exerted. Considering only the successful attempts, foraging with the hybrid foraging behaviour gathered more food than the novel foraging behaviour, but with more work exerted. Foraging with the hybrid behaviour resulted to complete forage occurring 75% of the time with respect to all the foraging attempts made, which was faster and more optimal than the case of the novel behaviour's, which occurred 67% of the time, but exerting more work. The hybrid proved to gather more food, and much faster, consistent and more optimal than the novel behaviour.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the novel behaviour gathers more food than the hybrid behaviour, but with more work exerted. Considering only successful attempts, both the novel and hybrid foraging behaviour gather roughly the same amount of food, but with the hybrid behaviour exerting lesser work. The novel foraging behaviour resulted to complete forage occurring for 49% of the total attempts, but slower than the case of the hybrid behaviour, which occurred for 38% of the total attempts. The hybrid behaviour proved to be faster and more optimal, but less consistent due to failed attempts. The novel behaviour proved to be more consistent and to gather more food.

4.2.1.4. Experiment 4 Analysis

This experiment was conducted for – three scouts, ten followers and a single food location.

- Open World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gathers more food than the novel foraging behaviour, with less work exerted. Considering only successful attempts, the hybrid behaviour gathers more food. Complete forage only occurred using the hybrid foraging behaviour for 1% of total attempts. The hybrid foraging behaviour proves to be better and more optimal than the novel behaviour in this experiment.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gathers more food than the novel foraging behaviour while exerting lesser work. Considering only successful attempts, the hybrid behaviour still gathers more food. No complete forage was observed in both cases. The hybrid foraging behaviour proved to be better, more optimal and more consistent than the novel foraging behaviour.

4.2.1.5. Experiment 5 Analysis

This experiment is conducted for – three scouts, thirty followers, and a single food source.

- Open World Experiment: - considering both successful and unsuccessful foraging attempts, foraging using both hybrid and novel behaviour gather roughly the same amount of food, but with the hybrid behaviour exerting lesser work. Considering only successful attempts, the hybrid behaviour gathers more food while exerting lesser work. Complete forage occurs in the hybrid behaviour for 68% of all attempts and occurs faster with less work exerted (more optimal) than the case of novel behaviour, which occurs for 45% of all attempts. The hybrid foraging behaviour proved to be better, more optimal, consistent and faster than the novel behaviour.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging using the novel behaviour gathers more food than the hybrid behaviour. Considering only successful attempts, the hybrid behaviour gathers more food than the novel behaviour, while exerting lesser work (energy). Complete forage occurs with both behaviours, but the hybrid behaviour occurs for 30% of all attempts, and faster and more optimal than the case of the novel behaviour, which occurs for 13% of all attempts. The hybrid behaviour proved more optimal, faster and more consistent than the novel foraging behaviour. The novel behaviour however gathers more food than the hybrid considering all possibilities.

4.2.1.6. Experiment 6 Analysis

This experiment is conducted for – three scouts, fifty followers, and a single food source.

- Open World Experiment: - considering both successful and unsuccessful foraging attempts, foraging using both the hybrid and novel behaviour gathers roughly the same amount of food, but with the hybrid foraging behaviour exerting lesser work (more optimal) than the novel behaviour. Considering only successful attempts, the hybrid foraging behaviour gathers more food than the novel foraging behaviour, while exerting lesser work (more optimal). Complete forage occurs with both behaviours but occurs in the hybrid behaviour for 86% of all attempts and more optimal than the case of the novel behaviour, which occurs for 75% of all attempts. They are both roughly matched in speed for complete forage, with the novel behaviour edging out to be marginally faster. The hybrid foraging behaviour proves to be better, more optimal and consistent than the novel foraging behaviour.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the novel behaviour gathers more food than the hybrid behaviour. Considering only successful attempts, the hybrid behaviour gathers more food than the novel behaviour, while exerting lesser work. Complete forage occurs with both behaviours but occurs in the novel behaviour for 63% of all attempts, and in the case of the hybrid behaviour, complete forage occurs for 48% of all attempts and is faster and more optimal than the novel behaviour's. The hybrid behaviour proves to be faster and more

optimal, but the novel behaviour proves to be more consistent and to gather more food given all possibilities.

4.2.1.7. Experiment 7 Analysis

This experiment is conducted for – a single leader, ten followers, and two food sources.

- Open World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gathers more food than the novel behaviour, while exerting lesser work. This is also true if only successful attempts are considered. Complete forage only occurs using the hybrid foraging behaviour, for 1% of all attempts. The hybrid behaviour proves to be better, more optimal and consistent than the novel foraging behaviour.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gathers more food than the novel behaviour, while exerting lesser work. This is also true if only successful attempts are considered. Complete forage does not occur with any of the behaviour. The hybrid behaviour proves to be better, more optimal and consistent than the novel behaviour.

4.2.1.8. Experiment 8 Analysis

This experiment is conducted for – a single leader, thirty followers, and two food sources.

- Open World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gathers more food than the novel behaviour, but exerting more work. Considering only successful attempts, foraging with the hybrid behaviour gathers more food than the novel behaviour while exerting more work. Complete forage occurs with both behaviours, where with hybrid behaviour it occurs for 79% of all attempts and is faster and more optimal than the case of the novel behaviour which occurs for 44% of all attempts. The hybrid behaviour proves to be better, faster and more consistent than the novel foraging behaviour. The novel proves to be more optimal in this experiment.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with both behaviours gathers roughly the same amount of food, but with the novel marginally more. The hybrid behaviour gathers these foods with lesser work than the novel behaviour. Considering only successful attempts, the hybrid behaviour gathers more food than the novel behaviour, while exerting lesser work. Complete forage occurs with both behaviours, but it occurs with hybrid behaviour for 45% of all attempts, and more optimal and faster than the case of the novel behaviour, which occurs for 24% of all attempts. The hybrid behaviour proves to be much better, faster, more consistent and more optimal than the novel foraging behaviour.

4.2.1.9. Experiment 9 Analysis

This experiment is conducted for – a single scout, fifty followers and two food sources.

- Open World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the novel behaviour gathers more food than the hybrid behaviour while exerting more work. Considering only successful behaviour, both behaviours gathers roughly the same amount of food. Complete forage occurs with both foraging behaviours, but it occurs with the novel behaviour for 84% of all attempts and faster than the case of the hybrid behaviour, which occurs for 73%, and is more optimal. Novel behaviour proves to be faster, more consistent and gathers more food than the hybrid behaviour. The hybrid behaviour on the other hand proves to be more optimal.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the novel behaviour gathers more food than the hybrid behaviour while exerting more work. Considering only the successful attempts, foraging with the hybrid behaviour gathers more food than the novel behaviour, while exerting lesser work. Complete forage occurs with both behaviours, but in the hybrid behaviour it occurs for 68% of all attempts and is faster and more optimal than the case of novel behaviour, which occurs for 63% of all attempts. The hybrid behaviour proves to be faster, more optimal and consistent than the novel behaviour, which proves to gather more food given all possibilities.

4.2.1.10. Experiment 10 Analysis

This experiment is conducted for – three scouts, ten followers and two food sources.

- Open World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gather more food than the novel behaviour, while exerting lesser work. This is also true if only successful attempts are considered. Complete forage only occurred with the hybrid behaviour, for 1% of all attempts. The hybrid behaviour proves to be better, faster, more consistent and more optimal than the novel behaviour.
- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gathers more food than the novel behaviour, while exerting lesser work. This is also true if only successful attempts are considered. Complete forage does not occur with both behaviours. The hybrid behaviour proves to be better, more consistent and more optimal than the novel behaviour.

4.2.1.11. Experiment 11 Analysis

This experiment is conducted for – three scouts, thirty followers and two food sources.

- Open World Experiment: - considering both successful and unsuccessful attempts, foraging with both behaviours roughly gathers the same amounts of food, where the amount from the novel behaviour edged higher. Although, the hybrid behaviour exerted lesser work. This is also true if only successful attempts are considered. Complete forage of the two food sources occurred with the hybrid behaviour for 8% of all attempts. Complete forage for a single food source occurred with both behaviours, but it occurred in the hybrid behaviour for 61% of all attempts and is more optimal than the case of the novel behaviour, where it occurred for 54% of all attempts, and is faster. The hybrid behaviour proves to be more consistent and more optimal than the novel behaviour, which proves to marginally gather more food and is faster.

- Obstacle World Experiment: - considering both successful and unsuccessful foraging attempts, foraging with the hybrid behaviour gathers more food than the novel behaviour while exerting lesser work. This is also true if only successful attempts are considered. Complete forage occurred with both behaviours, but it occurred in the hybrid behaviour for 42% of all attempts, and more optimal than the case of the novel behaviour, which occurred for 23% and was faster. The hybrid behaviour proves to be better, more optimal and more consistent than the novel behaviour.

4.2.1.12. Experiment 12 Analysis

This experiment is conducted for three scouts, fifty followers, and two food sources.

- Open World Experiments: - considering both successful and unsuccessful attempts, foraging with the novel behaviour gathers more food than the hybrid behaviour, while exerting more work. This is also true if only successful attempts are considered. Complete forage for a single food source occurred with both behaviours, but it occurred with hybrid behaviour for 82% of all attempts and is faster and more optimal than the case of novel foraging behaviour, which occurred for 81% of all attempts. Complete forage for the two food sources occurred with both behaviours for 3% of all attempts, but with the hybrid behaviour being faster but less optimal. The hybrid behaviour proves to be faster and more consistent than the novel behaviour, which proves to be more optimal and gathers more food.
- Obstacle World Experiments: -considering both successful and unsuccessful attempts, foraging with the novel behaviour gathers more food than the hybrid behaviour, while exerting more work. This is also true if only successful attempts are considered. Complete forage for a single food source occurs with both behaviours, where it occurred with the novel behaviour for 67% of all attempts, and in the case of the hybrid behaviour, it occurred for 64% of all attempts, and is faster and more optimal. Complete forage for the two food sources occurred with both behaviours, where it occurred with the hybrid behaviour for 2% of all attempts and is more optimal than the case of the novel behaviour, which occurred for 1% of all attempts and is much faster. The hybrid behaviour proves to be more optimal than the novel behaviour, which proves to be faster, more consistent and gather more food.

4.2.2. Conclusive Analysis

The experiments are conducted for both the novel behaviour and the hybrid foraging behaviour to take into consideration all possibilities, uncertainties and failures that can occur during physical implementation of swarm behaviours in artificial systems. This can be seen by Considering nest size, where the normal size for the foraging swarm would be between 20-30. Therefore, using 10 and 50 followers can be seen as an extreme situation where the swarm is a new colony of few members, and when the swarm is a matured colony with a lot of members.

From the results, we can observe that as the number of followers increase, the number of foods foraged and the speed of foraging increases. Inferences are made on the food foraged, speed, optimality and consistency of both the novel behaviour and the hybrid behaviour. The table presented below summarizes these inferences. One point is allocated for food foraged, speed, optimality and consistency by both the open world and obstacle world experiments that compose of the research experiments (1-12).

Table 2. *Conclusive Analyses*

	Hybrid Foraging Behaviour					**Novel Foraging Behaviour**			
	Food Foraged	**Speed**	**Optimality**	**Consistency**		**Food foraged**	**Speed**	**Optimality**	**Consistency**
1	2	2	2	2		0	0	0	0
2	1	1	2	2		1	1	0	0
3	1	2	2	1		1	0	0	1
4	2	-	2	2		0	-	0	0
5	1	2	2	2		1	0	0	0
6	0	1	2	1		2	1	0	1
7	2	-	2	2		0	-	0	0
8	2	2	1	2		0	0	1	0
9	0	1	2	1		2	1	0	1
10	2	2	2	2		0	-	0	0
11	1	0	2	2		1	2	0	0
12	0	1	1	1		2	1	1	1
Total	**14**	**14**	**23**	**20**		**10**	**6**	**2**	**4**

The table above shows that the hybrid behaviour is an improvement to the novel behaviour in terms of the number of foods that can be foraged, the speed it will take, its consistency in foraging as much as possible, and in its optimality in conducting the foraging task and performing work, like pheromone reinforcement. The optimality of the hybrid behaviour is the best trait of this behaviour as can be inferred directly from the results presented. The hybrid behaviour is likely to have more failed attempts at performing the foraging task than the novel behaviour, but the results show that even when the unsuccessful and successful attempts are both considered, there is an improvement that is made to the results from the novel behaviour. The research questions ask several questions about the performance and optimality of both behaviour, and these are answered below:

- Answer for Research Question 1: Using the results of both the open world and obstacle world experiments, the hybrid foraging behaviour will forage more food than the novel foraging behaviour. As the number of followers increase, the amount of food foraged increases.
- Answer for Research Question 2: As inferred from experiments and analysis, both foraging behaviours would forage an amount of food that are roughly the same or marginally more or less, but the hybrid behaviour would be more optimal. As the size increases the number of foods foraged increases. The more the leader agents, the faster the food source is found.
- Answer for Research Question 3: foraging with the hybrid behaviour gathered more food than with the novel behaviour. The number of foods foraged increases as the size of the forager agents increases.
- Answer for Research Question 4: Foraging with both behaviours would result to an amount of food that is roughly similar or marginally more or less than each other, where the hybrid foraging behaviour would be more optimal. The more the leaders and followers, the more the amount of food foraged.
- Answer to Research Question 5: Considering the obstacle world results only, the novel foraging behaviour would have more food foraged than the hybrid behaviour if both successful and unsuccessful attempts are both accounted for. But ideally, when all attempts are successful or only considered, foraging with the hybrid behaviour gather more food than the novel behaviour, and does this optimally.
- Answer to Question 6: Swarms that forage with the hybrid foraging behaviour uses its resources more optimally than the novel behaviour and is rewarded more than the novel behaviour. The hybrid behaviour is very optimal compared to the novel behaviour.
- Answer to Question 7: Swarms foraging with the hybrid behaviour perform their foraging tasks faster than the case of the novel behaviour. When a food source is exhausted, the time taken using the hybrid behaviour is smaller than that of the novel behaviour. Speed is the second-best trait observed in the hybrid foraging behaviour.

From the experiments, results and analyses, it can be inferred that the hybrid behaviour is more prone to failure but still out performs the novel behaviour. This will be discussed in the next chapter. The novel behaviour is not very consistent and optimal while foraging, and this can affect the practical feasibility of this behaviour. The next chapter discusses all these issues.

Chapter

5

DISCUSSION

This chapter presents discussion based on the research conducted and its results.

5. DISCUSSION

5.1. OVERVIEW

The realisation of swarm intelligence and other natural phenomena in artificial systems is nearer than ever. The swarm behaviour observed in natural swarm systems show a collective behaviour that is decentralised, but still display surprising attributes of self-organisation. This thesis investigated the foraging of ant swarms (fire ants), which is a swarm behaviour that emerges from simple interactions between ants and their environment or themselves, in order to retrieve food from food sources in their environment for the sustenance of the swarm. The aim of this thesis research was to discover the profitability of hybridizing models of natural phenomena for practical implementation, over the normal implementation of these models. The foraging behaviour of ants was hybridized with the flocking behaviour of avian flocks to compare with the natural foraging behaviour of ants in performing foraging tasks. These experiments were conducted in a developed environment that allowed for different scenarios and instances that concerned the swarm and its environment. As presented in detail in the previous chapter, the results of the hybrid foraging behaviour and the novel foraging behaviour were compared, and some inferences were made. From the inferences, answers to the research questions were presented. These showed several improvements that are made by hybridization, and also showed some negative effects. These are discussed in the next section.

The foraging behaviour of ants are described in chapter 2 and are closely replicated in the simulation experiments. The flocking behaviour, which is also described in chapter 2 is used to hybridize the ant's foraging behaviour. This hybridization is modelled and implemented to describe the hybrid foraging model. By taking these natural processes and replicating them in an artificial environment, the resultant processes or model would not be a perfect replication of the original or natural one. Hence, the comparison between the natural (novel) foraging behaviour and hybrid foraging behaviour tested the performance of using a single imperfect model, which is designed for the task of experimentation, and the performance of using two imperfect models that are hybridized to support each other, and therefore, draw out the best from each other. Remarkable results showed higher and improved performance with the hybridized model.

In general, with the hybrid behaviour, improved performance could be observed in terms of the work done, which is the number of foods foraged, the speed, the optimality and the consistency of its performance.

5.2. POSITIVE AND NEGATIVE EMERGENT BEHAVIOURS

Experiments that were conducted with the novel and hybrid behaviour took different scenarios into consideration in order to properly provide good results that can direct more future researches in the right direction. A single nest of constant size was used for the experiments, therefore, by changing the number of swarm members between high and low, and its composition and changing the nature of the environment, the extremities of the novel behaviour and hybrid behaviours were experimented on. These experiments drew out behaviours that were detrimental and rewarding to the foraging task for both behaviours.

5.2.1. Negative Emergent Behaviours

An important occurrence that can be observed by looking at the graphs presented in 4.1. is that at times when a food source is found, and pheromone trail created and reinforced, no food is foraged. This is observed in both the novel and foraging behaviours, and its occurrence increased when there are obstacles in the environment. This can be termed as unsuccessful forage. This shows the imperfection of these foraging behaviours, or indirectly shows the faults of the foraging behaviour of ants. There are different scenarios that surrounds this occurrence. The common scenario that applies to both behaviours is the early decay of the pheromone trail resulting to cutting off the nest from the food source. This occurrence is increased in the case of single scouts, because when a food source is cut off, the marker pheromones and the releaser pheromones in the food location decay. When this happens, the food source becomes discoverable for any other scout. But when a scout finds a food source, it starts the foraging process, and does not perform scouting again. Instead it performs the role of a follower from thereon. This behaviour makes the swarm to be inactive, once a scout is inactive. As hypothesized earlier, the queen ants indirectly influence the composition of its swarm, and when the number of scouts depreciates, the swarm starts to fare badly with respect to feeding. Hence, we can see a direct dependence of the swarm on the abilities, functions, and number of scouts.

The scouts play major roles in foraging, but once foraging begins, meaning that a scout has done its job, the followers then decide the fate of the task from thereon. Cutting off the pheromone trail results from the behaviours or scenarios that emerges from the followers. In this experiment, when the swarm members are of small number, it takes a long time before the releaser pheromone or recruitment pheromone is detected. These are the inducers of the behaviours that allow foraging to emerge, and without them or when decayed, nothing happens, and the foraging process dies off. An agent in the nest moves randomly in an attempt to detect the recruitment pheromone by chance. An agent in the food location moves randomly in an attempt to detect the releaser pheromone. When these pheromones are not detected, scenarios arise, where agents are not able to detect these pheromones, and the pheromone trail connecting them decays off below reinforcement threshold. A pheromone trail is made up of individual pheromones that form a chain, so when a trail decays, the pheromones that make up the trail decay individually. When this happens, pheromones that are placed earlier than the others decay faster than the others, and therefore if not reinforce quickly, it can decay enough to cut the pheromone trail into two or more parts. When agents do not reinforce the pheromone trail due to them being unlucky in detecting the releaser pheromones to travel along the trail, the trail can get cut off. These agents can be either in the food location or the nest. Say an agent as retrieved a food, and it detects the releaser pheromone, it leaves and starts to travel along the pheromone trail. It reinforces the pheromone as it goes. If this agent keeps travelling along the pheromone, but the pheromone trail is cut off, it will keep looping back and forth from its start point to the cut-off point, while reinforcing any decayed pheromone. When this scenario occurs, results with zero food foraged, but pheromone trail reinforced are presented. This leads to unsuccessful forage attempts.

In the case of hybrid foraging behaviour, other scenarios that can lead to this occurrence, apart from luck, are – (a) the conflict of opinions and (b) time for flock formation.

(a) Conflict of opinions – When agents form flocks in the active space of the recruitment pheromone, they do not just arrive at the recruitment pheromone at the same time. Each agent arrives at different times, and in these times the size of the recruitment pheromone changes due to decay, and in turn this gives them different opinions about the quality of the food source. As previously described in 3.2, this allows each agent to create a list of flock members that they recognise. The opinion they have is the number of flock members that will be suitable for the foraging task. When the flock leaves the nest, some members might leave the flock. When opinions are too diverse, the whole flock members can disperse. When this happens to much, some part of the pheromone trail does not get reinforced, and can decay so much, and result to cutting off the destination.
(b) Time to flock formation – When flock forms, time elapses, and the pheromone trail decays. When this happens pheromones that are placed early or not reinforced in a while, decay below reinforcement threshold, and therefore resulting to the trail cutting off into two or more parts.

Due to the other scenarios, the possibility of unsuccessful forage occurring in hybrid foraging behaviour is higher than the novel behaviour. As seen in the results, its occurrence is much higher in hybrid behaviour than in the novel behaviour, therefore, affecting its performance.

5.2.2. Positive Emergent Behaviours

Despite the negative behaviours seen from the experiments, there are positive behaviours that were observed. In the case of the novel foraging behaviour, consistency and redundancy is observed when challenged with obstacles. No matter how much an agent fails to successfully travel through the pheromone trail, the agent goes back to the nest, and luckily gets to try again. This process of failing and recovering is much faster in novel behaviour than the hybrid behaviour. Due to the obstacles, when scouts find a food source, they avoid them as they lay up pheromones, therefore creating safe passage for the swarm. These passages are more difficult than the ones in the open spaced world, hence, requiring extra effort from the agents that traverse it. Due to the redundancy and fast recovery, foraging with the novel foraging behaviour might tend to gather more food than the hybrid behaviour in a limited time-span, given this obstacles scenario. The hybrid foraging behaviour can fail and recover, by going back to the nest, and luckily forming a new flock. But this takes longer than the recovery in novel behaviour.

In the case of the hybrid foraging behaviour, behaviours like cooperation and profiting as described in 3.2, are observed and leads to other behaviours like optimal usage of resource, fast exhaustive forage of a food source, and good consistency. When agents forage with the hybrid behaviour, there is always an optimal use of resource that comes as a result of the cooperation exhibited among themselves. This cooperation (or profiting) allows the agents in a flock to access a food source and perform intense retrieval of foods in quick fashion. Working together to reach the food location or the nest helps the flock incredibly, because there are less failed attempts in traversing the pheromone trail. when the food location is reached, complete forage is more likely to occur, and given the opportunity, the flock consistently forage from these food source until it gets exhausted.

5.3. PRACTICAL FEASIBILITY

By comparing both foraging behaviours, inferences were made based on the number of foods foraged, the speed in which food is foraged, the optimality, and the consistency, and the hybrid foraging behaviour came out on top in all. The novel foraging behaviour replicates the natural foraging behaviour of ants and bringing this behaviour into artificial systems is not going to be a perfect process or implementation. The experiments show that the novel foraging behaviour is not so much concerned with the optimal usage of resources like its hybrid but focuses on the food to be foraged. Ants are natural lifeforms that can produce pheromones throughout their lives and use them as much as they want. The experiments showed how much pheromones are vital to the tasks undertaken by swarms, where the usage of pheromones does not put much focus on optimality, but on results. By observing experiments, one can notice that shortest path situations are solved by the processes that surrounds the pheromone and its usage. In simulation runs done previously in this work, two food sources are placed, where one is closer to the nest than the other.

While observing the swarm foraging from both food locations, it could be seen that the longer path decayed faster than the shorter one, because the time used or to be used in reinforcing the longer pheromone trail was higher. This can be described by the scenario: - two kids are walking back and forth from the sea shore, and one is walking a longer distance than the other. The water comes to wash away the foot trails periodically. The foot trail made by the boy walking the shorter distance would remain a more impressed mark on the floor, because he can reinforce his foot trail 3 or more times before the water sweeps through. The foot trail made by the other boy walking the longer distance would be more likely to be swept clean through, because the boy would be able to reinforce his trail once or less before the water sweeps through. Due to this the longer trail would not get reinforced often, and eventually the waves would wash them off or a part off. When this occurs in ant foraging, the short pheromone trail would remain and persist until foraging ends.

From the results, we could see that in almost all foraging activity, when foraging with the hybrid behaviour, more foods are gathered than the novel behaviour, and it’s done with lesser pheromone reinforced. This also happens when both behaviours gather the same number of foods. The best trait that can be observed in the hybrid behaviour is its optimality. When implementing systems and hardware for practical use, good optimality, speed, and consistency are very important features these systems should have. The practical benefits of the hybrid foraging behaviour are higher than the novel foraging behaviour, as seen in the results. With the types of complex applications that are arising in areas like: space exploration, mining, military, security etc. high levels of cooperation might be needed. The practical feasibility of the hybrid foraging behaviour tends to be better and more promising than that of the novel foraging behaviour.

Chapter

6

CONCLUSION

This chapter presents a summary and brief discussion derived from this research.

6. CONCLUSION

This research aimed to discover the profitability of hybridizing models of swarm intelligence or natural phenomena for implementation in artificial systems, over the normal implementation of these models in artificial systems. Experiments were conducted, and the results shows that the hybridization of these models can deliver promising behaviours and effects that can improve the practical implementations of these models. These models are bio-inspired models that attempt to replicate and describe natural processes and phenomena, but imperfectly. Implementing such models as is, has been the normal standard to follow.

In this research work, the foraging behaviour of ants was implemented in simulation and used to compare with a hybridization of the foraging behaviour of ants with the flocking behaviour of birds. This thesis predicted that there would be an improvement in the performance and optimality of the hybrid behaviour over the novel behaviour. Without the experiments conducted, the specifics of the outcomes cannot be easily discerned. However, after the behaviours (novel and hybrid) were modelled and implemented in simulations, extensive experiments were conducted, in order to account for many possible scenarios that can occur during practical implementations. The results of the experiments showed an overall improvement of the performance and emerged behaviour from the hybrid behaviour over the novel behaviour. The hybrid behaviour was not a perfect behaviour and still had its flaws, but the improvements made were significant. The results showed general improvements in work done, speed, optimality and consistency.

The results clearly show the promise of hybridizing models, and hopefully can facilitate more research.

6.1. LIMITATIONS

Due to limitations in time and resources, this research thesis conducted experiment with simple hybridization using a simple hypothesis that described the bird flocking behaviour. Despite that, the results show incredible promise. This research was aimed at discovering the effect and profitability of using hybridization in practically implementing swarm intelligence or phenomena. Unfortunately, there were no hardware implementations in this research that would have confirmed the improvements and beneficial effects of the hybridization in real world scenarios and use cases.

6.2. RECOMMENDATIONS AND FUTURE WORKS

The implementation of swarm intelligence in artificial systems is an ongoing research. This thesis suggests that the hybridization of models should be worked on, as the results here show that promising effects, benefits and improvements can be attained. In this work, the hybrid foraging behaviour, made use of a simple bird flocking model/hypothesis to hybridize the ant's foraging behaviour. The hybridization of the ant foraging behaviour with better models of flocking or schooling can lead to better results. The description given by Reynolds in [37], shows and impressive model for flocking and schooling. This model can be hybridized into the novel foraging behaviour to get better results and accommodate for any inefficiencies seen the chorus – line hypothesis of avian flocks.

The behaviours of swarms and their base processes are in-exhaustive, because there is an emergence down from their individual biology to the swarm activities and characteristics they portray. There are large ranges of applications that can be derived from swarm intelligence or behaviours and hybridizing these swarm behaviours can lead to more interesting applications. To advance this research, a practical implementation would suffice, as this can help in properly experimenting and analysing the influence or effects of hybridization. There are other researches and projects that have made use of hybridization [18] to gain different benefits.

The implementation of artificial intelligence and robotics gain inspiration from nature and life. Swarm intelligence has been a field that has been gaining momentum, as researchers aim to exploit its benefits. As observed in this research, stigmergy is an important (vital) characteristic of swarm intelligence. Most natural swarms make use of pheromones to facilitate stigmergy. The artificial swarms that are being developed in order to function like these natural swarms, face hindrances in exploiting stigmergy. This can be resolved down to not knowing the form in which the medium of stigmergy would take or formed. In natural swarms, ants produce pheromones, and employ it to facilitate stigmergy. In artificial swarms, what do the robots or agents produce or what can be produced, that can be used to facilitate stigmergy? This question has indirectly hindered the progression of research in swarm intelligence, but the answer lies in man's ecology, as it laid in ants' ecology and biology also.

Ecology influences the evolution of the base processes which are extensively used in swarms, therefore to create swarm-inspired robots and systems, we must consider our current Ecology. Our ecology is extremely composed of EM waves of varying frequencies and ranges. This tells us that the artificial pheromones are already all around us and is in use, hence propelling the future of swarm robots along this line would be beneficial. We can also deduce that the era of the Internet of Things would play vital role in swarm robotics and the communication between individuals in the swarm or swarms, and the communication between these swarms and the world around them.

Chapter

7

REFERENCES

This chapter presents a list of research works that has been studied and helped in influencing this research and was cited.

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APPENDIX

This presents the results, and additional information (algorithm) that was used in conducting this research and experiments.

8. APPENDIX

8.1. RESULT TABLES

8.1.1. Open World Results for Novel and Hybrid Behaviours

8.1.1.1. General Results

Table 3. *Open World - General Results for Novel foraging Behaviour Experiments*

	Number of foods foraged	Number of times pheromone is reinforced	Number of foods foraged (successful forage only)	Number of times pheromone is reinforced (Successful forage only)
		One food source		
Experiment 1	21.2603	287.2055	-	-
Experiment 2	39.9219	315.8281	-	-
Experiment 3	45.2174	275.7681	-	-
Experiment 4	22.9158	352.2211	23.4086	356.3978
Experiment 5	44.2813	376.5729	44.7474	378.0737
Experiment 6	47.3187	357.0549	47.8444	358.8222
Average	**37**	**327**	**37**	**329**
		Two food sources		
Experiment 7	22.1395	254.6977	22.4	256.3176
Experiment 8	43.0253	255.3291	-	-
Experiment 9	48.4318	255.1364	-	-
Experiment 10	32.12	484.31	-	-
Experiment 11	62.2	529.83	-	-
Experiment 12	69.28	519.87	-	-
Average	**46**	**383**	**46**	**384**

Table 4. *Open World - General Results for Hybrid foraging Behaviour Experiments.*

	Number of foods foraged (Average)	Number of times pheromone is reinforced (Average)	Number of foods foraged (Average) (successful forage only)	Number of times pheromone is reinforced (Average) (Successful forage only)
		One food source		
Experiment 1	27.4333	227.6333	28.8772	232.3333
Experiment 2	46.3103	275.7414	47.1228	275.7368
Experiment 3	44.6935	284.3226	47.7759	284.8448
Experiment 4	31.2421	332.7368	31.5745	333.0213
Experiment 5	44.7732	329.7938	46.6989	334.0538
Experiment 6	47.1684	306.0947	48.7065	309.587
Average	**40**	**293**	**42**	**295**
		Two food sources		
Experiment 7	33.4773	228.6705	-	-
Experiment 8	46.1758	259.2747	48.2989	265.0115
Experiment 9	43.5595	209.25	47.5195	215.2857
Experiment 10	39.73	443.61	40.9588	446.4124
Experiment 11	61.01	422.36	61.6262	425.2222
Experiment 12	59.63	396	61.4742	397.9175
Average	**47**	**326**	**49**	**330**

8.1.1.2. Complete Forage Results

This present results in tables which shows how fast a food source was completely foraged, and the number of times pheromone reinforcement occurred during the foraging task.

Table 5. *Open World -Complete forage results for single a food source (50 food items) for Novel foraging behaviour.*

	Number of times pheromone reinforcement occurred (Average)	Complete foraging time (Time-steps) (Average)	Number of times Complete foraging occurred (Percentage)
One food source			
Experiment 1	-	-	-
Experiment 2	442.5455	11197.32	34.375
Experiment 3	308.1522	10008.07	66.667
Experiment 4	-	-	-
Experiment 5	429.5116	11505.37	44.7917
Experiment 6	383.9848	8994.348	72.5275
Average	**391**	**10,426**	
Weighted Average	**379**	**10,166**	
Two food sources			
Experiment 7	-	-	-
Experiment 8	299.3143	11350.97	44.3038
Experiment 9	275.9459	8926.365	84.09
Experiment 10	-	-	-
Experiment 11	514.4444	10049.28	54
Experiment 12	505.7531	8224.16	81
Average	**399**	**9,638**	
Weighted Average	**400**	**9,346**	

Table 6. *Open World – Complete forage results for single a food source (50 food items) for Hybrid foraging behaviour.*

	Number of times pheromone reinforcement occurred (Average)	Complete foraging time (Time-steps) (Average)	Number of times Complete foraging occurred (Percentage)
One food source			
Experiment 1	-	-	-
Experiment 2	284.6364	11626.77	75.8620
Experiment 3	302	9804.128	75.8065
Experiment 4	437	12481	1.053
Experiment 5	330.8939	9954.652	68.0412
Experiment 6	328.2561	8998.695	86.3157
Average	**336**	**10,573**	

Weighted Average	**311**	**10,072**	
Two food sources			
Experiment 7	396	14967	1.136
Experiment 8	278.5139	10100.57	79.1209
Experiment 9	208.8197	9008.492	72.619
Experiment 10	296	13763	1
Experiment 11	401.1475	8777.574	61
Experiment 12	379.9878	7305.695	82
Average	**326**	**10,654**	
Weighted Average	**315**	**8,817**	

Table 7. *Open World – Complete forage results for two food sources (100 food items) for Novel foraging behaviour*

	Number of times pheromone reinforcement occurred (Average)	Complete foraging time (Time-steps) (Average)	Number of times Complete foraging occurred (Percentage)
Two food sources			
Experiment 12	505.7531	6652	3

Table 8. *Open World – Complete forage results for two food sources (100 food items) for Hybrid foraging behaviour*

	Number of times pheromone reinforcement occurred (Average)	Complete foraging time (Time-steps) (Average)	Number of times Complete foraging occurred (Percentage)
Two food sources			
Experiment 11	556.58	10444.25	8
Experiment 12	624.3333	5788.333	3
Average	**590**	**8,116**	
Weighted Average	**575**	**9,174**	

8.1.2. Obstacle World Results for Novel and Hybrid Behaviour

8.1.2.1. General Results

As stated in the previous section, results presented on "successful forage only" provides results where foraging was successful. A food Location can be found, but no foraging occurs due to different scenarios. This results to unsuccessful foraging.

Table 9. *Obstacle World – General Results for Novel foraging Behaviour Experiments*

	Number of foods foraged (average)	Number of times pheromone is reinforced (average)	Number of foods foraged (Average) (successful forage only)	Number of times pheromone is reinforced (Average) (Successful forage only)
		One food source		
Experiment 1	15.4211	275.197	16.0548	280.5068
Experiment 2	32.2714	303.2838	32.2714	306.9429
Experiment 3	43.4306	352.7639	-	-
Experiment 4	14.7895	346.5684	15.6111	352.0778
Experiment 5	34.8163	371.8265	-	-
Experiment 6	45.1122	425.8367	-	-
Average	**31**	**346**	**31**	**348**
		Two food sources		
Experiment 7	15.7340	243.798	16.076	245.804
Experiment 8	37	302.073	37.787	303.096
Experiment 9	43.47	269.42	43.95	270.69
Experiment 10	23.26	460.15	23.5	463.1
Experiment 11	50.98	522.62	-	-
Experiment 12	63.64	580.11	-	-
Average	**39**	**396**	**39**	**398**

Table 10. *Obstacle World – General Results for Hybrid foraging Behaviour Experiments.*

	Number of foods foraged (Average)	Number of times pheromone is reinforced (Average)	Number of foods foraged (Average) (successful forage only)	Number of times pheromone is reinforced (Average) (Successful forage only)
		One food source		
Experiment 1	17.5652	319.957	20.8966	325.9483
Experiment 2	28.889	304.873	41.3636	348.4545
Experiment 3	33.0635	277.349	44.3192	313.9574
Experiment 4	18.7802	328.593	21.9103	331.0513
Experiment 5	30.4167	338.844	41.7143	369.0714
Experiment 6	34.8210	344.126	47.257	373.7
Average	**27**	**319**	**36**	**344**
		Two food sources		
Experiment 7	20.2921	250.551	24.08	258.92
Experiment 8	35.6	253.727	41.77	251.33
Experiment 9	39.56	250.345	45.89	247.61
Experiment 10	28.64	446.25	31.82	454.07
Experiment 11	52.27	486.61	55.61	489.89
Experiment 12	51.91	468.08	58.326	480.16
Average	**32**	**359**	**43**	**364**

8.1.2.2. Complete Forage Results

This section presents results of experiments where a food source was foraged until exhaustion.

Table 11. *Obstacle World -Complete forage results for single a food source (50 food items) for Novel foraging behaviour.*

	Number of times pheromone reinforcement occurred (Average)	Complete foraging time (Time-steps) (Average)	Number of times Complete foraging occurred (Percentage)
One food source			
Experiment 1	-	-	-
Experiment 2	426.2222	13304.89	11.84
Experiment 3	425.4571	11190.91	48.6111
Experiment 4	-	-	-
Experiment 5	460.6154	12651.15	13.265
Experiment 6	437.0806	9674.1	63.265
Average	**437**	**11,705**	
Weighted Average	**434**	**10,796**	
Two food sources			
Experiment 7	-	-	-
Experiment 8	311.783	11371.35	23.96
Experiment 9	284.458	9850.847	63.441
Experiment 10	-	-	-
Experiment 11	516.04	10224.26	23
Experiment 12	575.75	8708.70	67
Average	**422**	**10,039**	
Weighted Average	**429**	**9,663**	

Table 12. *Obstacle World – Complete forage results for single a food source (50 food items) for Hybrid foraging behaviour.*

	Number of times pheromone reinforcement occurred (Average)	Complete foraging time (Time-steps) (Average)	Number of times Complete foraging occurred (Percentage)
One food source			
Experiment 1	-	-	-
Experiment 2	381.625	11386.92	38.095
Experiment 3	356.917	10929.75	38.095
Experiment 4	-	-	-
Experiment 5	395.7	11284.62	30.208
Experiment 6	390.5	9601.37	48.42
Average	**381**	**10,801**	

Weighted Average	**381**	**10,698**	
Two food sources			
Experiment 7	-	-	-
Experiment 8	250.73	10597.33	45.45
Experiment 9	256.75	9769.71	67.82
Experiment 10	-	-	-
Experiment 11	500.76	10388.57	42
Experiment 12	466.73	8559.23	64
Average	**369**	**9,829**	
Weighted Average	**364**	**9,704**	

Table 13. *Obstacle World – Complete forage results for two food sources (100 food items) for Novel foraging behaviour*

	Number of times pheromone reinforcement occurred (Average)	**Complete foraging time (Time-steps) (Average)**	**Number of times Complete foraging occurred (Percentage)**
Two food sources			
Experiment 12	785	9638	1

Table 14. *Obstacle World – Complete forage results for two food sources (100 food items) for Hybrid foraging behaviour*

	Number of times pheromone reinforcement occurred (Average)	**Complete foraging time (Time-steps) (Average)**	**Number of times Complete foraging occurred (Percentage)**
Two food sources			
Experiment 12	726.5	10257.5	2

8.2. NOVEL BEHAVIOUR AND HYBRID BEHAVIOUR ALGORITHMS

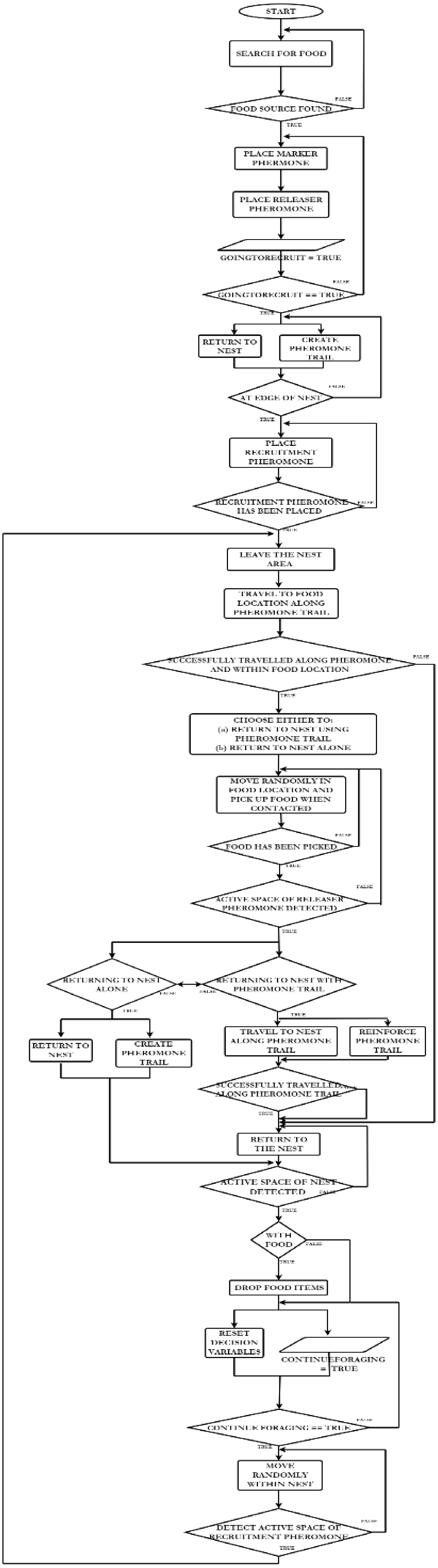

Figure 64. *Novel Behaviour – Scout agent*

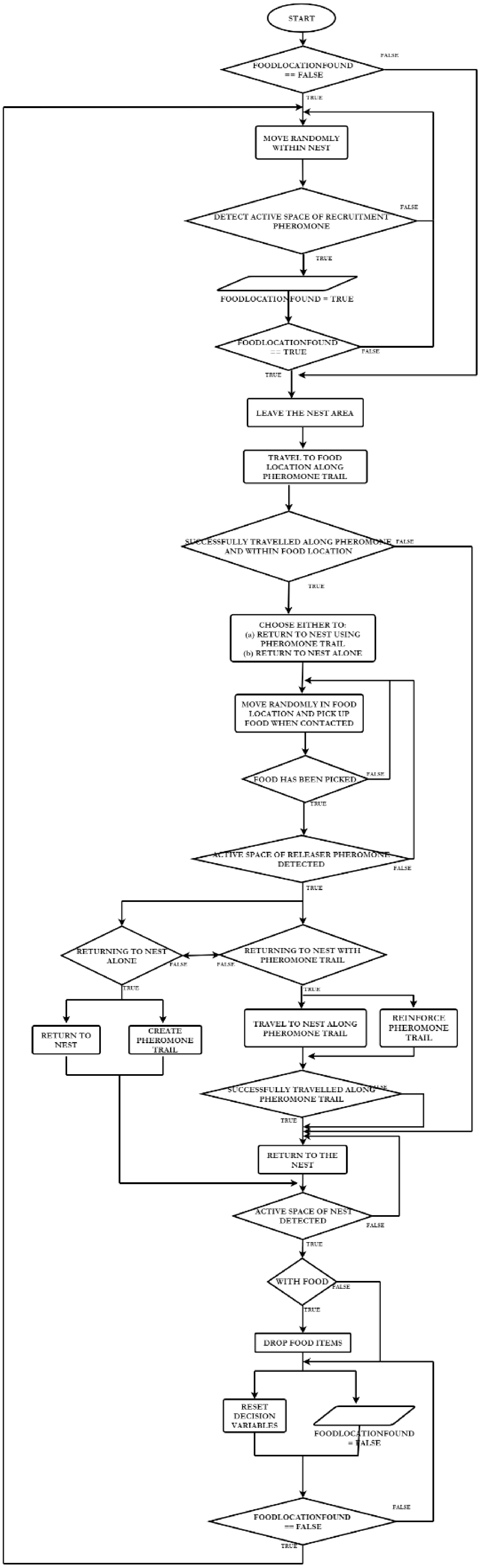

Figure 65. *Novel Behaviour - Follower agent*

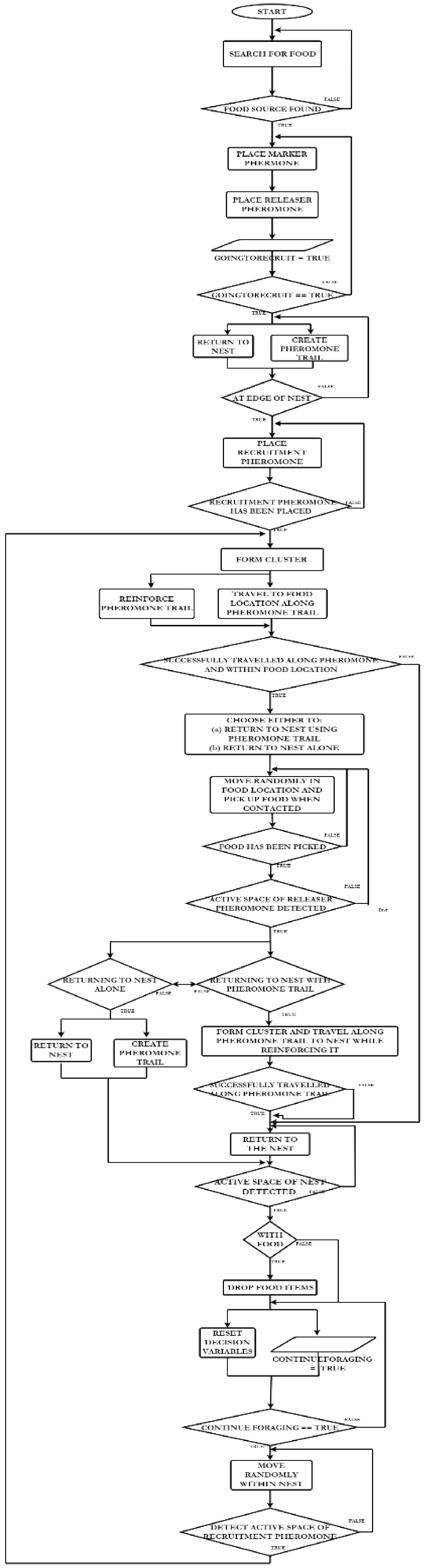

Figure 66. *Hybrid Behaviour – Scout Agent.*

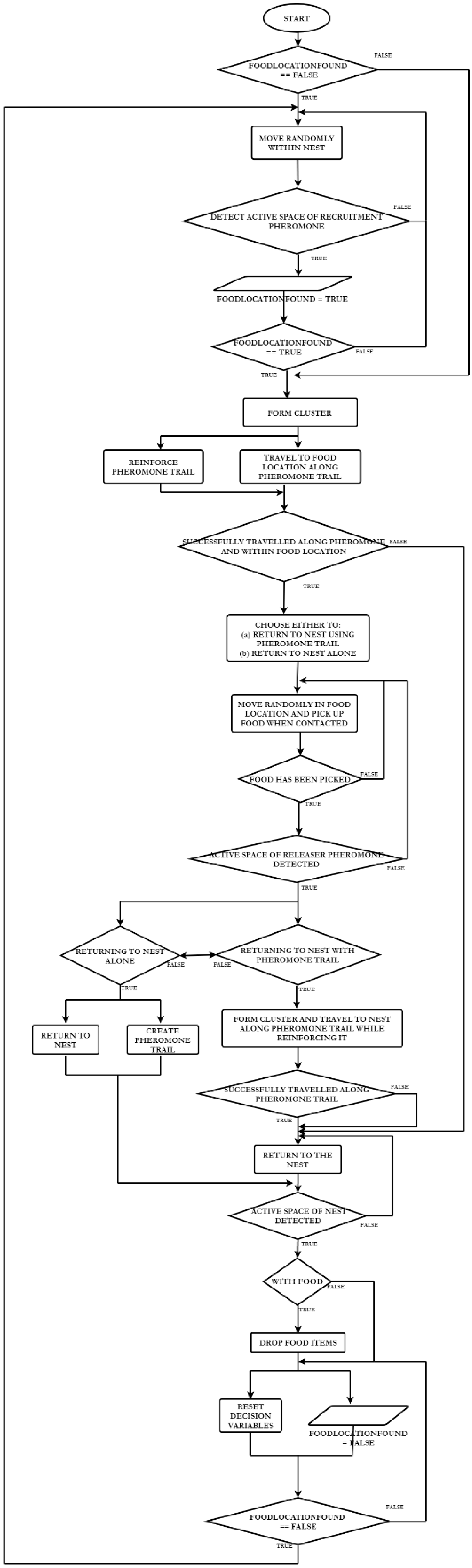

Figure 67. *Hybrid Behaviour – Follower agent*