AN INVESTIGATION INTO THE DESIGN OF AN ANTS-INSPIRED ONTOLOGY FOR COORDINATING PATHFINDING ROBOTIC DEVICES

by

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DECLARATION

I, Shirindi Ntshuxeko, Student Number 202112339, hereby declare that:

1. I have read and understood the Sol Plaatje Policy on Plagiarism and the definition of plagiarism.

2. Accordingly, all quotations and contributions from any source whatsoever (including the Internet) have been cited fully. I understand that the reproduction of text without quotation marks (even when the source is cited) is plagiarism.

3. I declare that the work contained in this mini-dissertation is my own, and that the mini-dissertation has not been accepted for any other degree and is not concurrently submitted in the candidature of any other degree.

Signature:  Date: 20 November 2023

DEDICATION

This work is dedicated to Sol Plaatje University, to my supervisor, my classmates, and my family for their support, encouragement, and inspiration throughout this journey.

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ABSTRACT

Swarm intelligence systems, wherein robotic devices are created with abilities executed at individual level to create swarm level emergent behaviour, are appealing to industries such as nanotechnology, amorphous computing, and engineering. They are often considered suitable for determining solutions to computationally complex problems within a context where large, sophisticated robots are too expensive to procure. For instance, bee colony models, fish schooling solutions, and ant colony systems have been proposed for solving complex problems by imitating the behaviours of related natural species. Ant colony systems, in particular, have been used to offer solutions to complex optimisation issues such as the traveling salesman problem, the vehicle routing problem, and the bridge crossing task. Compelling robust and fault tolerant solutions have been produced and reported. However, formal representation of the knowledge of the ant-like robotic devices thereof has not been fully explored. In this context, ant-like robotic devices are interchangeably referred to as ant-bots. An ant-bot, on its own, may not have capabilities to accomplish notable solutions to problems. However, as a swarm, ant-bots can produce compelling emergent behaviour more than the sum of the actions of the individual ant-bots in the swarm. This study proposed the development of an ontology for characterising the low-level behaviours and capabilities of simulated ant-like robotic devices tasked to path find. First, we considered the distinctive qualities of ant-bots and found out that foraging is key. Ant-bots require five key actions; dropping pheromone-like indicators, flipping between different internal states, orientating based on the amount of the virtual pheromone within their local environment, making informed movements when it becomes necessary, and no action as self-explanatory. The key meta needs include the environment that holds information about the targets, and pheromone dissipation attributes. Data flow diagrams, entity relationship diagrams, and Warnier-Orr figures were derived as part of the ingredients for the proposed ontology. The study investigated the validity of the ontology that arose from the study through a triangulated mix of

simulations, experimentation, and data visualisation. Precisely, three experiments were administered to evaluate the usefulness of the proposed ontology. Speed of emergence was the main metric for this assessment. Visual emergent behaviour augmented the outcomes obtained from evaluating speed of emergency. Also, assessment of the resource demand from using the ontology sealed the evaluations. Results indicated that the proposed ontology captured and represented the knowledge required by ant-bots to achieve path finding. The ontology provided a knowledge representation approach for swarms of ant-like robotic devices, providing a roadmap to the low-level behaviours of ant-bots towards convergence. Representation of swarm knowledge in the form of an ontology offers the potential to reshape the field of swarm robotics. Such formal knowledge representation technique brings about effectiveness, adaptability, and reliability in swarm systems.

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Chibaya, C and **Shirindi, N**. 2023. Simulated Ant-agent Aspects for Defining an Ant-bots Ontology. In the proceedings of the Nineteenth International Conference on Autonomic and Autonomous Systems. ICAS 2023. https://www.iaria.org/conferences2023/ICAS23.html, Barcelona. Spain.

Shirindi, N; Madzima, K. and Chibaya, C. 2021. Face Recognition using PCA and constrained images. In the 2021 3rd International Multidisciplinary Information Technology and Engineering Conference (IMITEC). Added to the IEEE Xplore Digital Library on the 21st of February 2022. e-ISBN:978-1-6654-1749-5.ISBN:978-1-6654-1750-1.DOI:10.1109/IMITEC52926.2021.9714604

CHAPTER 1: INTRODUCTION

1.1 Background

Swarm intelligence is a branch of artificial intelligence that focuses on understanding the behaviour of natural social groups such as colonies of ants, swarms of bees, flocks of birds, or schools of fish (Selvi & Umarani, 2010). It is an approach to problem-solving inspired by the distinct traits of natural phenomena (Dorigo, Birattari, & Stutzle, 2006). For example, artificial ant systems have been built and have received attention in various application areas (Frank, Hönle & Linsenmair, 2018) because of the robust and fault tolerant solutions they achieve. The way anthills, ant nests, or coordinated path formation emerge from the cooperative actions of natural ants is compelling and inspiring. What is the knowledge of each natural ant that causes such plausible emergent behaviour? What does each ant in the swarm do to contribute to the ultimate goal of the swarm? What has related literature done to capture and formally represent such knowledge for easy application and reproducibility?

Literature indicates that attempts have been made to emulate ant behaviour in computational terms. For example, Chibaya and Mugari (2021) successfully presented routines for coordinating ant-like robotic devices towards establishing the shortest path between a nest-like starting point and a food-like target. Dorigo et al. (2007) administered the bridge crossing experiment to validate shortest path formation behaviour in ant systems. Although these discrete solutions are encouraging, formal knowledge representation in this domain has been overlooked.

The need to understand swarm intelligence systems, in general, is becoming a niche research area (Dorigo et al., 2007). This is because swarm intelligence models have been considered appropriate for finding approximated solutions to computationally complex problems, where large complex robots are too expensive to procure. Attempts to understand the natural swarm systems which give rise to emergent behaviour to emulate the same in artificial swarm models are coming at the right time when we need solutions to life changing problems. In this context, emergent behaviour is defined as swarm-level behaviour that emanates from the individual actions of the swarm members (Mittal & Rainey, 2015).

Ant models are visible. However, the knowledge of ant-like robotic devices in simulated ant systems that cause emergent behaviour is still blurred. Moreover, the language ant-bots use to communicate with one another in simulated systems when they cooperate to solve problems, is overlooked. There is lack of a clear formal methodology for representing this knowledge domain. The need for a more formal knowledge representation approach, some kind of a language for ant-bot, is apparently required.

As a case study, this study sought an understanding of the component units of simulated ant-inspired swarms in which ant-bot can cooperate towards path finding and path following behaviour. In this context, path finding behaviour is the coordinated movement of a simulated ant-bot from one location to another, using the shortest path around obstacles. The critical actions of ant-bot, which cause this emergent behaviour in computational terms, are the key deliverables to the study reports, together with their parameters and definitions of how they are used by these robotic devices. We contextually refer to this envisioned deliverable as the ants-inspired ontology. Precisely, an ants-inspired ontology is the formal knowledge representation for the component units of artificial ant systems. The envisioned ontology is more like an ant’s dictionary comprising environment information, heuristics data, and the ant-bot actions. Representing these critical component units in the form of an ants-inspired ontology will potentially propel the application of this problem-solving paradigm in real life and in the industry.

1.2 Rationale

Robotic devices are increasingly used to solve problems in exploration, environmental monitoring, surveillance of buildings, and medicine (Fahimi, 2019). One rationale for undertaking this study was the desire to participate in this bona fide adventure. Hopefully, we were able to verify the claim that an ants-inspired ontology can provide an explainable mechanism for coordinating ant-like robotic devices toward successful path finding. It was enticing to participate in this challenge of creating practical swarm intelligence systems that directly address the technical advancements to reshape the ICT industry. The desire to join the leaders in advancing the fourth industrial revolution agenda further motivated us to undertake this study.

The application of most robotic systems converges around reducing human involvement in the future (Ojstersek & Veber, 2017). Hopefully, robotic devices would, one day, solve tasks in situations where humans are uncomfortable. Robotic devices would also bring about more accountability related to product quality and time at work. It is envisioned that robotic devices would not request for leave, take a day off, or go on vacation. It is satisfying to participate in such a journey.

1.3 Problem statement

Understanding the aspects of ant systems that give rise to emergent behaviour, and proposing a formal knowledge representation mechanism for ant systems, constituted the thrust of the issues tackled in this study. If we get to successfully identify the primitive aspects of ant systems that cause path finding behaviour, then we can formally represent the knowledge domain. An understanding of this knowledge domain may inspire practical solutions to swarm-based problems. The problem statement of this study is, therefore, the development of an ants-inspired ontology for achieving path finding emergent behaviour.

1.4 Aim of the study

The aim of the study was to investigate the discrete aspects of simulated ants that cause emergent behaviour and propose the same in the design of an ants-inspired ontology for coordinating path finding ant-like robotic devices. To do so, we sought to put those aspects, parameters, rules, and relationships together into useful ontology designing tools such as entity relationship diagrams, data flow diagrams, and Warnier Orr diagrams. The proposed ants-inspired ontology was built from these ontology designing tools before it was tested for successfully resolving the path finding problem.

1.5 Objectives of the study

Four objectives summarize the aim of this study are as follows:

1. To identify the actions of simulated ant-like robotic devices with causal properties to the path finding and path following emergent behaviour. These actions were derived from the literature.
2. To investigate the interpretation of the identified primitive actions in algorithmic terms. Precisely, how do we program each critical robotic device's action? In this case, code snippets were identified.
3. To design an ants-inspired ontology for path finding emergent behaviour. In this case, we investigate how all aspects are put together into a knowledge representation format (the ontology) that can inspire swarm intelligence. To achieve this, data flow, entity relationship, and Warnier Orr diagrams were used as the basis for the proposed ants-inspired ontology.
4. To evaluate the ants-inspired ontology's usefulness in causing the path finding emergent behaviour as well as achieving visually appealing emergent behaviour. These evaluations were augmented through an assessment of the technical needs (memory demands) of the model.

1.6 Research questions

Four research questions emanate, aligned to the four objectives listed in section 1.5 above. These questions are:

1. What are the primitive actions of simulated ant-like robotic devices that demonstrate causal properties to the path finding and path following emergent behaviour?
2. How do we interpret the proposed ant actions in computational or algorithmic form?

3. How do we represent the knowledge of ant-like robotic devices for coordinating the path finding emergent behaviour?
4. To what extent does the proposed ants-inspired ontology effectively cause visually appealing path finding emergent behaviour?

1.7 Hypothesis

This study is a hypothesis testing exercise, where a null hypothesis (H_0) and an alternative hypothesis (H_1) compete for acceptance at a 95% level of confidence. These two hypotheses are stipulated as follows:

H_0: The actions identified as primitive to the behaviour of simulated ant-like robotic devices do not have any significant effects to the swarm's path finding emergent behaviour. This can be interpreted to insinuate that the proposed ants-inspired ontology does not influence the path finding emergent behaviour observed in simulated swarms of ant-like robotic devices. Key would be to check for evidence to accept or refute this claim.

H_1: The actions identified as primitive to the behaviour of simulated ant-like robotic devices cause the path finding emergent behaviour we observe in swarms of ant-like robotic devices. This is translated to mean that the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour observed in swarms of ant-like robotic devices.

The bulk of the work undertaken going forward was geared towards seeking evidence to accept or reject the null hypothesis over the alternative hypothesis.

1.8 Expected outcomes.

There are five envisioned deliverables that will likely emanate from this study. These deliverables include, in any order, the following:

- A list of ant-like robotic device's primitive actions.

- Pieces of codes that interpret ant-like robotic device actions in algorithmic form. These codes are the building blocks of the ontology and any related applications thereto.
- The ants-inspired ontology to represent the domain of ant-like robotic devices knowledge. In our views, the ontology will create a baseline upon which advanced applications of ant systems may ensue.
- The mini – dissertation that reports the findings of this study. This mini – dissertation adds to the literature in the body of knowledge.
- A conference paper has already been born from this study. Hopefully, another publication in an accredited journal may be added, which will report the key results and findings of the study.

It is important to note that the study reported in this mini – dissertation does not go as far as deploying physical robotic devices in real-world environments due to costs and time implications. Instead, the study focuses on proposing and testing the ants-inspired ontology in virtually simulated environments. Extension of the work to real – world contexts will remain as future work.

1.9 Research ethics statement

The study concentrated on the understanding of simulated primitive actions of ant-like robotic devices. These primitive actions were mined from the literature on swarm intelligence systems. There was no direct contact with real ants in nature. Computational implementation of ant-like robotic devices' primitive actions in NetLogo was the primary task. In this case, NetLogo is an open-source software development platform for free and educational purposes.

The procedure through which the project was developed followed the standard software development life cycle. Any code was implemented on a stand-alone PC and tested on the same PC. The study did not pose any danger to people, animals, or any organization in the world. The experiments administered in the study were all solely to demonstrate the validity of the proposed ontology in causing the simulated path finding emergent behaviour. This study did not do anything to mislead individuals, Sol Plaatje University, or any other stakeholders deliberately. The work remained objective, sticking to the facts, and discussing the findings as they emerged. All the results reported from the study remained authentic. We maintained honesty and truthfulness, and always embraced the study's integrity.

1.10 Chapters layout of the mini dissertation

The mini dissertation is divided into five chapters as illustrated in Figure 1.1.

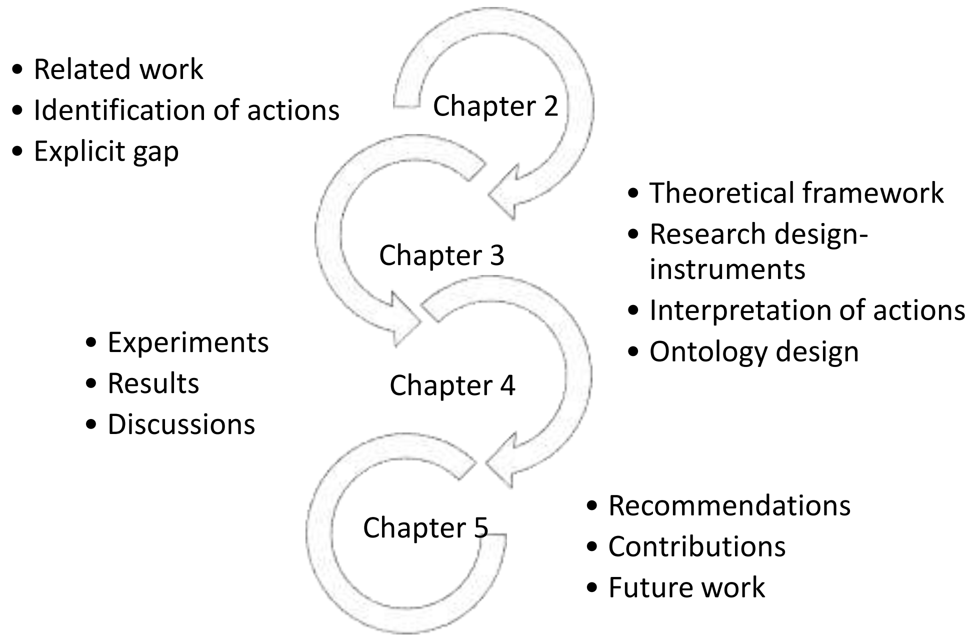

Figure 1.1 Chapters layout

Chapter 2 presents related work, drawing attention to earlier attempts to develop ant swarm systems, as well as identifying the insinuated key primitive actions of simulated ant-like robotic devices. In Chapter 3, we describe our procedures and the theoretical framework that underpins the reasoning and argumentations shared in the work. We also share our instruments, including the sampling procedure, experimental setup, functional requirements, requirements elicitation, evaluation approaches, data collection, recording, and reporting procedures. Chapter 4 presents the experiments administered to validate the proposed ontology. The results and findings are discussed in detail in this chapter. Also, visualised evidence of emergent behaviour is shown. Chapter 5, then summarises the study and provides the key recommendations, contributions, and any directions for future work.

1.11 Summary of the chapter

The chapter introduced the study by giving the background and rationale. It explicitly shared the problem statement and the aim of the study. Particular objectives were set, along with the related research questions. The study provided the hypotheses we tested, before dwelling on the envisioned deliverables of the study, as well as the ethics statement thereof. Chapter 2 will proceed with the reviews of related works.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to respond to objective number 1 of this study (see section 1.5 of this document). To achieve that, I reviewed literature, looking for primitive actions of simulated ant-like robotic devices. This chapter reviewed research interventions that attempted to address the formal knowledge representation of the ant systems problem substantively and methodologically. In the past, many authors have tried to develop swarm intelligence ontologies inspired by the functionalities of ant colony systems. Early attempts were also noted in Dorigo, Birattari & Stutzle's (2006) work when they presented simulated ant-like robotic devices critical actions that caused the emergent bridge crossing behaviour. In their work, the significance or function of the trail pheromone stood out. Trail pheromones were proven effective guides to the simulated ant-like robotic devices (Dorigo et al., 2006). This understanding of trail pheromone's function as simulated ant guides was confirmed and underwent numerous modifications and improvements (Malhotra, 2017). In the context of this present study, trail pheromones are equally an important or critical component to consider in the design of the desired ontology.

2.2 Layout of the chapter

The chapter proceeds as follows:

- Section 2.3 identifies the problem solved using the ant colony system.
- Section 2.4 specifically identifies the ant-like robotic device's primitive actions for the designing of the proposed ontology.
- Section 2.5 specifically identifies the knowledge gap we hope to fill in the body of knowledge.

- Section 2.6 summarizes what was covered to conclude this chapter.

2.3 Problem addressed

Ant colony systems have been used to solve complex optimisation issues, particularly in the field of computer optimisation, such as the traveling salesman problem, vehicle routing challenges, network routing, minimum spanning tree, and bridge crossing jobs. The ant colony system was found useful in complex optimisation issues by allowing one to arrive at almost optimal solutions quickly. The problems were solved regarding time and shortest path optimisation to the target. The technique's strength is its ability to effectively explore solution spaces and identify good answers even for difficult situations where other methods fail.

2.4 Identification of ant-like robotic device actions

It emerges in literature that ant-like robotic devices comprise an internal state to store the basic knowledge of the ant colony (Wang, Fan & Ding, 2014). Each ant-like robotic device is assumed to be constantly aware of its target, attractive levels of trail pheromone, repulsive levels, and existence of some nest-like point (Wang, Fan & Ding, 2014). Ant-like robotic devices would then flip between different internal states depending on their mission at the time whether they should be finding the target or returning to the purported nest-like point (Wang, Fan & Ding, 2014). Flipping between internal states by the ant-like robotic devices occurs as a reward for achieving a set goal, for example, hitting a target. We, therefore, note the importance of internal state in the design of the anticipated ontology.

In their stochastic decisions and movements around the environment, simulated ant-like robotic devices are envisioned to be dropping and updating specific levels of trail pheromone (Dorigo et al., 2006). When searching for the target, simulated ant-like robotic devices drop and update those levels of trail pheromone with directional information towards the nest-like point (Maniezzo, Gambardella & De Luigi, 2004). On the contrary, when navigating to the nest-like point, simulated ant-like robotic devices drop and update those trail pheromone levels with cues toward the found target (Dorigo et al., 2006). Trail pheromone updates are always heuristically applied through the dissipation process to improve the quality and speed of swarm convergence in simulation (Wang, Fan & Ding, 2014). Thus, dropping trail pheromone would be a primitive action of simulated ant-like robotic devices to include in the ontology.

According to research by Wang et al. (2014), most ant systems accomplish mission planning by repeatedly detecting, dropping, and updating trail pheromone at each step. They use their internal state transition to heuristically manage content awareness. In this case, successful orientation and subsequent movements in appropriate directions are a consequence of the previous actions. These discussions lead us closer to identifying the key component units of simulated swarm systems, the component units we require to design an ants-inspired ontology. In this context, movement is a key ingredient of the proposed ontology.

An investigation aimed at identifying the precise primitive actions of simulated ant-like robotic devices successfully used the ant nesting box in a laboratory (Yusuf, Crewe & Pirk, 2013). The goal was to gain an understanding of ant systems for adaptation towards solving more complex problems (Deepa & Senthilkumar, 2016), such as optimisation issues, self-organisation modelling (Balasubramaniam et al., 2006), or handling multi-agent innovative systems (Deepa & Senthilkumar, 2016). These studies are imperative as they align to, and further motivate, the undertaking of this study.

Some studies have focused on understanding ant systems' theoretical underpinnings (Dorigo & Blum, 2005). They endeavour to understand the theoretical foundations of swarm convergence. Are they the stochastic processes that drive the convergence process? Plausibly emerged, and these can be recommended for inclusion in the design of the ants-inspired ontology (Dorigo, Di Caro & Gambardella, 1999; Novikov & Novikov, 2013).

2.4.1 Summary of primitive actions.

This chapter identified five primitive actions of the simulated ant-like robotic devices that cause emergent behaviour. I identified primitive actions such as dropping off trail pheromone, orientating to choose the next direction stochastically, movement from one location to another, switching between internal states, and no action. The identified primitive actions are essential for the design of the suggested ants-inspired ontology.

2.5 The gap.

Research on formal swarm knowledge representation is lagging. We seek to turn to the use of ontologies to address this gap in the literature. Ontologies may attend to the sluggish improvements we observe in this field (Pagliarini & Lund, 2017). They may bring about computational intelligence techniques and new opportunities for swarm systems. Ontologies will question the drive, the crucial activities that direct ant-bot towards their actions (Colorni, Dorigo & Maniezzo, 1992), how swarm controls are achieved (Chibaya, 2019), as well as the parameters and attributes of all the component units involved. In our view, an ontology would holistically clarify the knowledge of the swarm and its formal representation. Precisely, more is needed to bring a plausible solution to the ant-like robotic devices knowledge representation in the form of an ants-inspired ontology, which is the focus of this study. Precisely, this study sought to clearly define the salient features of ant systems that can influence the design of an ants-inspired ontology. The actual gap this study sought to contribute to the body of knowledge on specificity and pertinency in the design of an ant-inspired ontology as a formal knowledge representation method in this domain. This study aimed to pinpoint the discrete aspects of ant systems that cause emergent behaviour, and evaluate the usefulness of the proposed ants-inspired ontology for coordinating path finding ant-like robotic devices.

This study emphasizes the implementation of the primitive actions of ants-like robotic devices for coordinating path finding emergent behaviour. This study sought to address the lack of a comprehensive ontology or framework that draws inspiration from ants' natural coordination capabilities to enhance the effectiveness of robotic devices tasked to achieve path finding. In our view, the study contributes to the body of knowledge by offering the potential to reshape the design of swarms. The suggested ants-inspired ontology will enhance multirobotic systems' efficiency, flexibility, and dependability. An explicit ants-inspired ontology will likely be effective and significance to the fourth industrial revolution.

2.6 Summary of the chapter

This chapter reviewed the literature on identifying the primitive actions of simulated ant-like robotic devices that cause emergent behaviour (achieving objective 1 of the study). Five lower-level activities of simulated ants were identified as dropping off trail pheromone, orientation, switching between internal states, movement, and taking no action when it becomes necessary. These primitive actions are the key ingredients for the design of the proposed ontology.

The gap we sought to fill was pinpointed as a search for the formal representation of the knowledge inferred in swarm systems. The next chapter, Chapter 3, presents the methods used to accomplish the study aim.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter discusses the procedures utilised to achieve the study's goal. The study- focus was the design of an ants-inspired ontology for coordinating path finding robotic devices. An ontology, in this case, is a formal knowledge representation of the component units of ant-like robotic devices. To design our ontology, we studied how these aspects identified in Chapter 2 might be combined into a single knowledge representation domain. These will be accomplished utilising tools such as entity relationship diagrams, data flow diagrams, and Warnier Orr diagrams. The ultimate combination of these diagrams constitute the proposed ants-inspired ontology that was tested to see if it properly resolves the path finding challenge.

This study was quantitative because we used numbers to determine whether the proposed ants-inspired ontology caused the path finding's emergent behaviour or not. The data collected in this study was about the performance of ant-like robotic devices when they utilise the identified primitive actions to achieve path finding emergent behaviour. This data was collected while simulating the identified ant-like robotic devices' primitive actions. The findings were measured in terms of speed, emergent behaviour, and resource demand. These findings (speed, emergent behaviour, and resource demand) were statistically examined to identify central tendencies, variability, correlations, and inferential statistics. The same data were intended to demonstrate the true nature of robotic device performance when the identified ant-like robotic devices' primitive actions were used. Hypothesis testing was used to draw conclusions.

3.2 Layout of the Chapter

The remaining chapters go as follows:

- Section 3.3 discusses the theoretical framework we worked within. It describes what this study is and is not about.
- Section 3.4 discusses the study area.
- Section 3.5 discusses the research design. It focuses on how primitive actions are interpreted in computational terms.
- Section 3.6 discusses the system design. It explains the software used in this study.
- Section 3.7 discusses the logical design. It focuses on the tools used to visualise complicated information for better understanding.
- Section 3.8 discusses the proposed ants-inspired ontology the study aimed to design.
- Section 3.9 concludes the chapter with a summary.

3.3 Theoretical framework

Interpretive thinking is a school of thought that understands the universe as being made up of human experiences, with participants' perspectives and backgrounds helping to reveal reality (Ponterotto, 2005). In this paradigm, judgments are drawn based on the opinions or feelings of those involved. This was not the purpose of the study. This research used quantitative results from systematic, well-structured scientific studies whose data were amenable to statistical analysis. We did not employ a paradigm that values interpretation. Instead, we embraced positivism, which is the paradigm and school of thought that best characterises what we did.

According to positivism, theories and hypotheses are tested by predictions based on law-like patterns (Heidtman et al., 2000). According to Ormston et al. (2014), positivists place a strong emphasis on the objectivity of the research process, rejecting the researcher's subjective opinions. These viewpoints align with the goals and objectives of this research. Specifically, our goal was to design an ants-inspired ontology for coordinating path finding robotic devices. Next, we sought to test our ontology for speed, emergent behaviour, and resource demand when ant-like robotic devices are used to accomplish a foraging task.

Inductive thinking is implied by an inductive method (Heit, 2000). The procedure moves from observations to theories (Pathirage et al., 2008). No guidelines are adhered to reach a conclusion. As a result, the results are based on observations rather than rules. It proceeds from ideas, observations, to generalisations. This study is not at all like that. Instead, we arrived at a conclusion using scientific methods.

A deductive approach focuses on establishing hypotheses based on existing ideas and then running experiments to test those assumptions (Casula et al., 2021). Principles, norms, ideas, and concepts are offered first, followed by their application (Casula et al., 2021). Deductive reasoning begins with a predicted pattern, then axioms, and finally, a theory that leads to a new hypothesis. This new hypothesis is tested for acceptance or rejection at predetermined significance levels. This research focused on the design of an ants-inspired ontology for coordinating path finding robotic devices. We wanted to be able to test the validity of the ontology regarding speed, emergent behaviour, and resource demand that occurs when the identified primitive actions are utilised.

This study can thus be summarised as falling under the design science research theoretical framework commonly found in the positivism paradigm. The study was quantitative, where we used an analysis process to accept or reject our hypothesis. The study involved statistical techniques to examine and control numerical facts. Statistical methods are used for hypothesis testing (Yilmaz, 2013).

3.4 Study area

This study focused on Swarm Intelligence, a subfield of artificial intelligence. We focused on the software side of the design of ant-like robotic devices, emphasizing the simulation of the primitive actions of ant-like robotic devices.

3.5 Research design

An ants-inspired ontology was designed as a proof of concept. Ant-like robotic devices were the main artifact of interest. Another artifact to consider was the environment where ant-like robotic devices occur. In this work, the main area of focus was the process of writing code for both building the environment and controlling ant-like robotic devices placed within the environment. Every ant-like robotic device in the swarm carries out the primitive actions identified in the literature review, which together comprise the swarm language. Each ant-like robotic device in the swarm should be able to execute these primitive actions in the correct order, with the correct parameters, and at the right time.

The focus was on the validation of the proposed ants-inspired ontology. The ant-like robotic devices were deployed on the environment, foraging for food-like targets. In evaluating the effectiveness of the ontology, this study experimented with many iterated tests on speed, emergent behaviour, and resource demand.

Statistical procedures are used to extract information from data (Eicher et al., 2020). The performances of the ant-like robotic devices were the key data analysed in this study, emphasizing speed, emergence behaviour, and resource demand. Graphs were utilised to understand these results and evaluate the ontology performance. The conclusion was drawn based on those findings.

3.5.1 Requirements elicitation

Requirements elicitation refers to the collection and definition of the software system requirements to meet the study goal. This ensures that the software development part is fulfilled and is suitable for the intended use of the experiment.

3.5.2 Functional Requirements

Functional requirements refer to how primitive actions are interpreted into computational routines. It is an opportunity to pinpoint the parameters of the primitive actions. In these interpretations, we assume that simulated ant-like robotic devices can indirectly learn from one another without directly and physically interacting with one another (Chibaya, 2015; Johnson, 2002).

3.5.2.1 Dropping trail pheromone

Dropping trail pheromone is a fundamental primitive action of ant-like robotic devices (Dorigo, Di Caro & Gambardella, 1999; Dorigo & Stützle, 2003; Panait &

Luke, 2004; Nakamichi & Arita, 2005; Chibaya, 2014; Dorigo & Stützle, 2019). We understand dropping trail pheromone to mean the retrieval of the amount of pheromone currently held at the ant-like robotic device's location, and updating the same levels of pheromone by topping it up by a certain quantity. Computationally, this primitive action is coded as follows:

```
DropPheromone (int Qty)
{
    CurrentPheromone = Read Current_level on location
    UpdatedPheromone = CurrentPheromone  + Qty
    Current_level on location = UpdatedPheromone
}
```

3.5.2.2 Orientation

Orientation is about an ant-like robotic device stochastically choosing the next direction to follow, based on the amount of trail pheromone held in the nearby locations. This is done before the simulated ant-like robotic device moves. Ant-like robotic devices have eight possible directions to move to (Chibaya, 2014; Corne et al., 1999; Mei et al., 2006).

```
Orientate ()
{
  forEach Robotic Device
  {
          forEach Location around the robotic device
          {
                  X =  AmtAttractivePheromone
                  Y =  AmtRepulsivePheromone
                  LocationWeight = X/Y
          }
          Spin RouletteWheel
   Direction = Hit by RouletteWheet in LocationWeight
  }
}
```

To orientate, the ant-like robotic devices determine the relative attraction of the trail pheromone held at each of the eight neighbouring locations (Panait & Luke, 2004). The location with a higher level of trail pheromone will be more favoured than the one with lower trail pheromone. In code terms, the quantities of trail pheromone are weighted into a roulette wheel. Locations with higher quantities will have a longer band in the roulette wheel than those with lower quantities. A random number within the roulette range is picked. That location corresponding to the band where the random number falls is stochastically picked.

An illustration of a roulette wheel setup is shown in Figure 3.1 below, where each location size corresponds to a scaled attractiveness rating for the corresponding position. The roulette wheel rotates clockwise from locations 1 to 8. The X on the roulette wheel indicates each location's attractiveness level. In this diagram, location 7 is more favoured than other locations because its arc length is the longest.

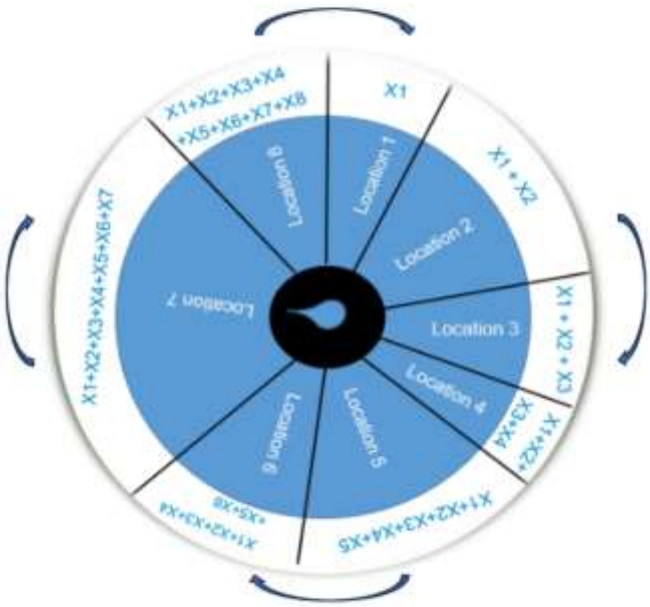

Figure 3.1 Roulette wheel

3.5.2.3 Movement

Upon successful orientation, an ant-like robotic device should relocate to the chosen location. In ant systems, the ability to move is essential for carrying out swarm-level tasks (Scheidler, Merkle & Middendorf, 2006; Chibaya, 2015). Movement is an autonomous activity at the individual level.

For simulated ant-like robotic devices to move from one location to another, it relocates to the new (*x,y*) by updating its coordinates. This can be interpreted in computational terms as follows:

```
Move ()
{
  forEach Robotic Device
  {
          Orientate ()
          X = x+ Orientate (x)
          Y = y + Orientate (y)
    }
}
```

3.5.2.4 Switch state

Ant-like robotic devices can flip between different internal states depending on their task at the time (Di Caro & Dorigo, 1998; Dorigo & Stützle, 2019; Coleman, Rothwell & Ross, 2004). Switching between internal states means the ability of ant-like robotic devices to change from either searching for a food-like target, to returning to the nest-like point, or vice versa. This occurs when the condition that triggers the ant-like robotic devices to switch from the current internal state to another is true. Also changes to different internal states take place as a reward for achieving some goal. By default, ant-like robotic devices are deployed in the search mode.

```
Switch_internal_state ()
{
        if Searching () and atGoal ()
                Internal_state = Return
        Else if Homing () and atNest ()
                Internal_state = Search
        Else
```

Internal_state =atHome () or atNest()

}

The visualised view of an ant-like robotic device's internal state is shown in Figure 3.2 below.

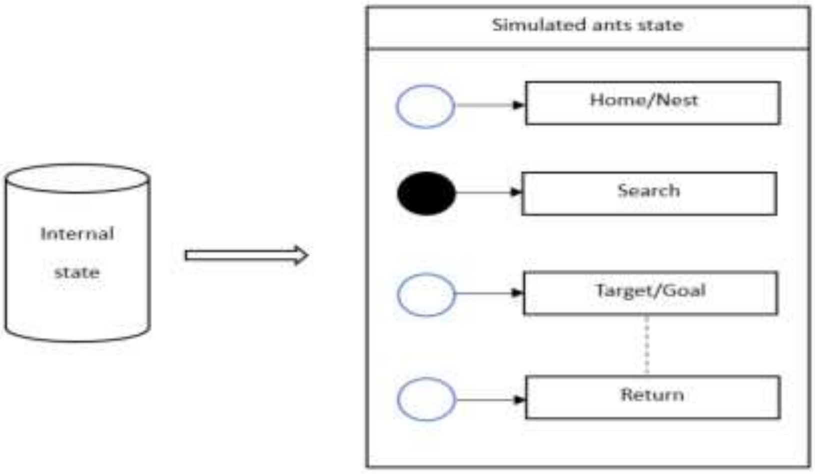

Figure 3.2 Ant-like robotic device internal states

3.5.2.5 No action

No action is self-explanatory. This primitive action indicates that it is possible that an ant-like robotic device may not engage in any activity at some points in time. This then insinuates a black routine.

3.6 System modelling

System modelling refers to the explanation of how a system functions. We used NetLogo as the implementation platform for the artifacts and routines.

3.6.1 Technical specification

NetLogo is an open-source platform for simulations. It enables the building of dynamic, interactive models to better comprehend complex systems and emergent behaviour. NetLogo can allow a strong foundation for system requirements elicitation through rapid prototyping of complex models. Figure 3.3 illustrates the user interface on experiments conducted. In the context of this study, the user interface comprises a plot, slider, buttons, and the environment. The plot visualises the food-like targets that ant-like robotic devices will seek to locate. The slider allows users to adjust the number of ant-like robotic devices in the swarm, trail pheromone diffusion rate, and trail pheromone evaporation rate. Contrary, the setup buttons let users reset the environment before the foraging task begins. The go button allows users to run the simulation. The environment comprises various entities such as the food-like target (pink, yellow, orange) cycles, the nest-like starting home (brown triangle), the ant-like robotic devices themselves (marked as a black dot), and the obstacle (set up as a red line). The environment's objects can all be moved around and positioned at any location in the area.

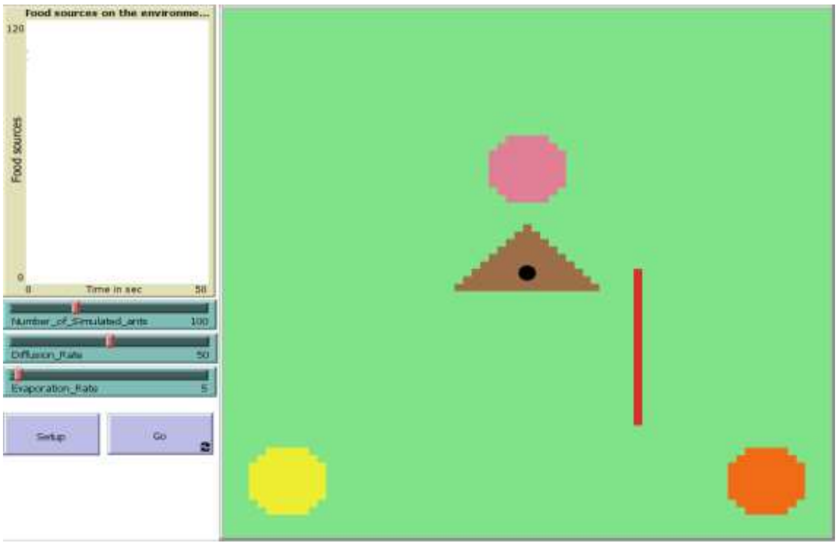

Figure 3.3 NetLogo user interface

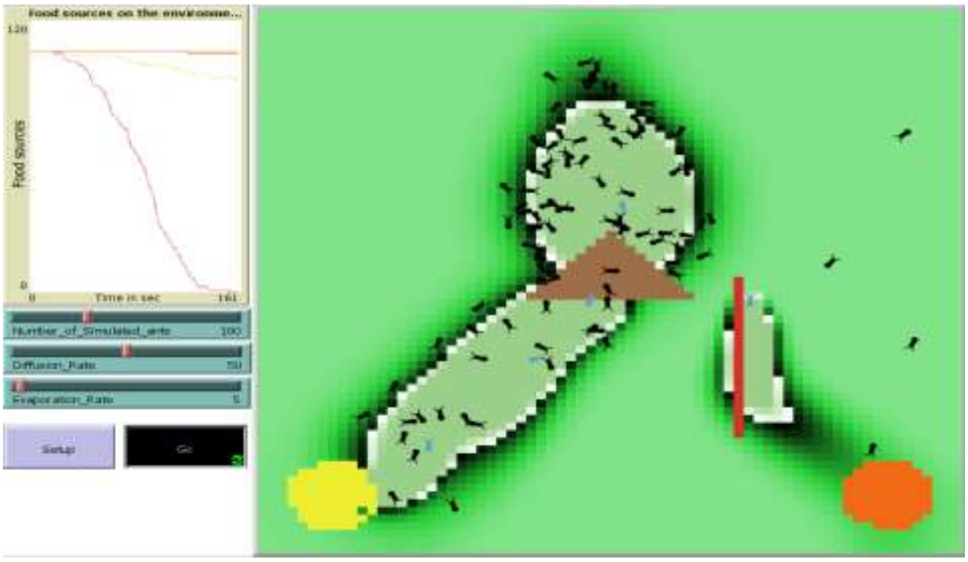

Figure 3.4 Foraging behaviour

Figure 3.4 visualises the path finding behaviour that emanates from running the model with a population of 100 ant–like robotic devices. The black ant-like robotic devices are still in the searching internal state. They are still to locate the food-like target. However, the blue ant-like robotic devices have found the food-like target and are now in the returning internal state, travelling back to the nest-like starting point. The dark green colour on the environment represents the trail pheromone created by these ant-like robotic devices as a communication medium.

The plot shows three curves representing the food-like target collection rate. The pink curve that reached the ground shows the completed collection of food-like target 1, which in fact, was closest to the nest-like starting point. The yellow and orange curves indicate ongoing food-like target collection, with collection at food-like target 2 (yellow) better than at food-like target 3 (brown) because of the impeding obstacle.

3.7 Logical design

Logical designs refer to the visualised design of the main entities of the system, the data involved, the outputs, relationships, and data flow. In this case, we focused on three logical designs, namely; the Entity-Relationship Diagram, the Data Flow Diagram, and the Warnier-Orr Diagram, each having a specific function in the demand elicitation process. These logical designs ensure an easy path from theory to practice, by helping us visualise, model, and organise the key components of the proposed ants-inspired ontology.

3.7.1 Entity-Relationship Diagram

Ant-like robotic devices' primitive actions are the basis of the entity relationship diagram proposed in this section. Each robotic device is designed with abilities to navigate the environment, and drop off trail pheromone to indirectly communicate with fellow robotic devices in the swarm. The entity relationship diagram we present is associated with ant-like robotic devices' path finding behaviour. During their foraging journey, robotic devices indirectly interact with one another through the environment. Thus, the environment is an important entity of the system. It is the shared memory and a dynamic stage in which the actions of the robotic devices are traced.

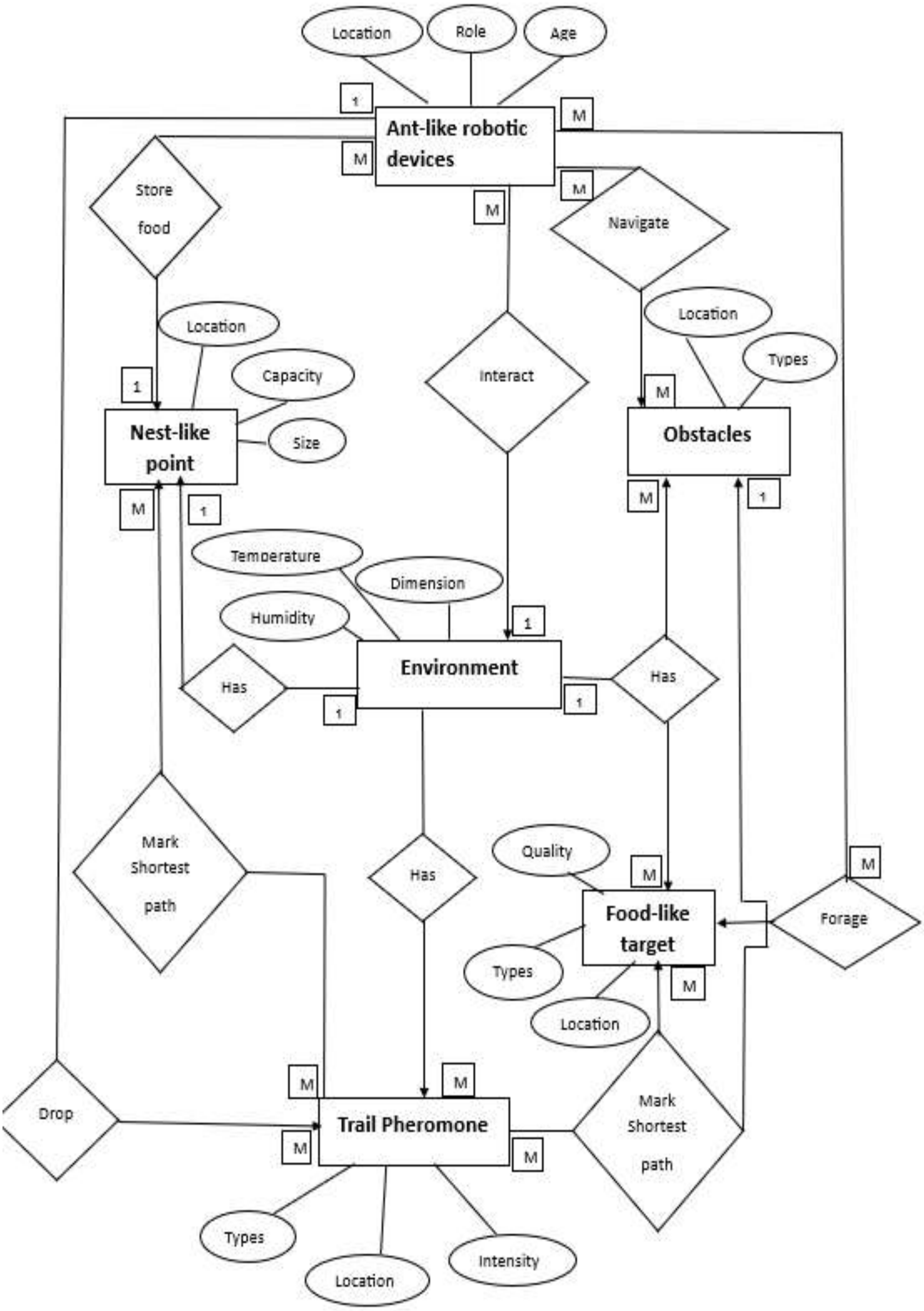

Figure 3.5 Entity relationship diagram

The Environment comprises four components: the Food-like targets, Nest-like point, Obstacles, and trail pheromone. Food-like targets are what robotic devices search for. The nest-like point is a location where robotic devices dwell when they are not doing anything. An obstacle, in this case, represents some form of barrier in the environments that ant-like robotic devices should navigate around. Trail pheromone, as already explained, marks trails through which indirect communication is achieved. The environment, thus, achieves a delicate balance of possibilities and obstacles, influencing the behaviour of the robotic devices, and encouraging their creativity.

Trail pheromones serve two purposes. Firstly, they mark the paths, directing ant-like robotic devices towards their targets at the time. Upon finding their targets, they mark trails back to the Nest-like point. Secondly, trail pheromones also define areas covered by obstacles in the environment. Figure 3.5 visualises the relationships between the entities of ant systems.

3.7.2 Data Flow Diagram

The key data shared in ant systems are pheromone trails. Trail pheromone guides ant-like robotic devices towards targets and away from obstacles. The concentration of trail pheromone insinuates the attractiveness of a path, leading to the establishment of the shortest path between the food sources and the nest-like point.

The environment works as a collective memory space for the swarm. It stores the relevant data. The data stored in the environment includes the trail pheromone, shortest path, obstacle’s location, food-like target location, and nest-like point location. The trial pheromone is the main update of all the activities taking place in the environment. The shortest path updates which path to take to the food-like target and back to the nest-like point. The obstacle location gives a warning on the path covered with a barrier. The food-like target updates which location ant-like robotic devices collect targets. Nest-like point updates where food-like targets are stored. The ant-like robotic devices use this information to make decisions and stay up to date, by reading what is on the current location.

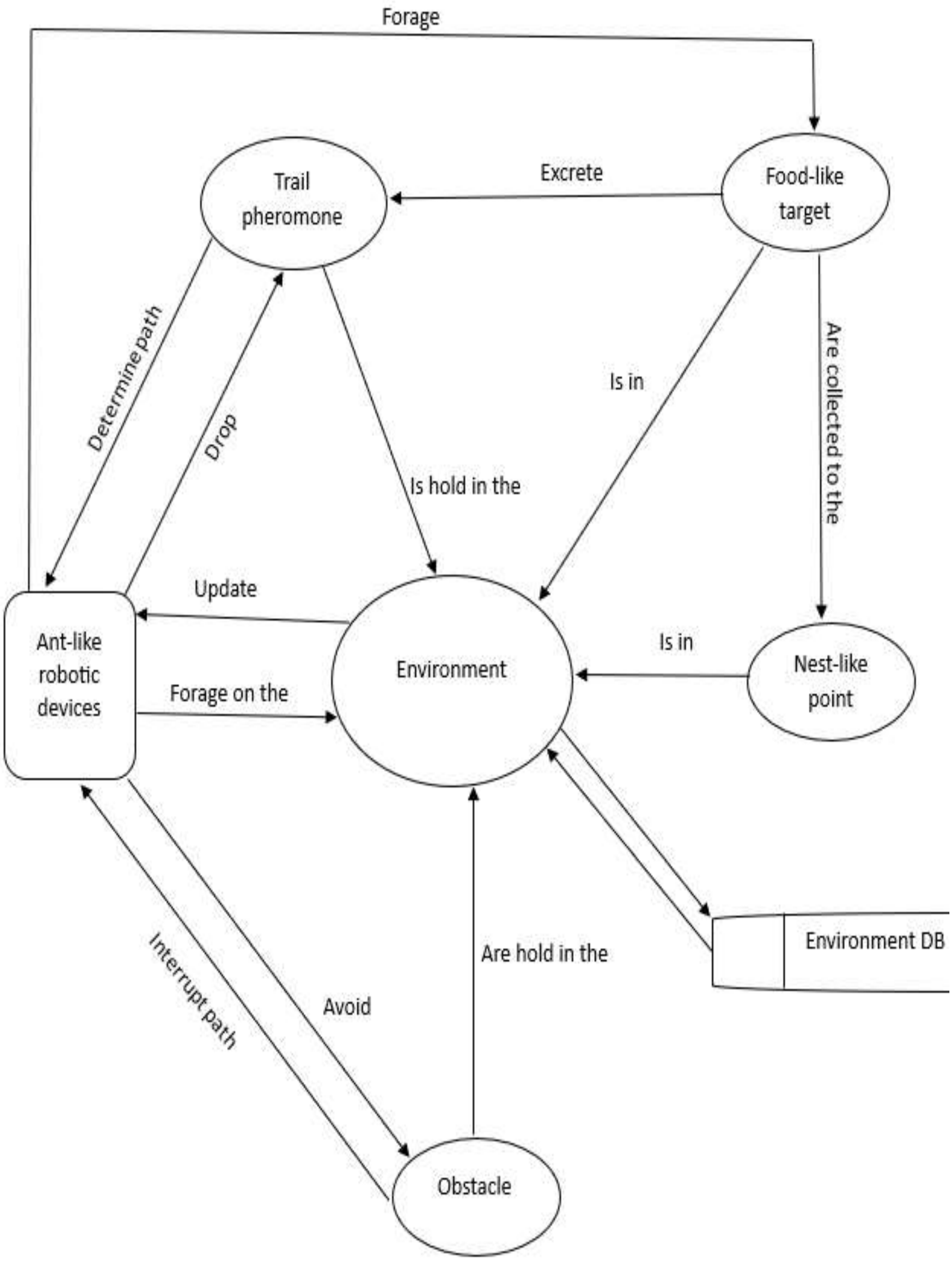

Figure 3.6 Data flow diagram

Trail pheromone plays a significant role in ant-like robotic device communication. Ant-like robotic devices complete foraging tasks due to the effectiveness of the trial pheromone on the environment. Trail pheromone level increases when ant-like robotic devices keep updating while using the same path, and decreases when no update is taking place. This significantly prevents ant-like robotic devices from using the same path, even when the foraging task is completed. Figure 3.6 visualises the data flow of the ant systems.

3.7.3 Warnier Orr Diagram

This section depicts the hierarchical relationship between the entities and data items of ant systems. The environment is the basis of the existence of ant systems. Within the environment, many robotic devices are deployed. There would be at least one food-like target and strictly one nest-like point. In this case, at least one obstacle is allowed. The environment also holds the levels of trail pheromone that would have been shared for swarm use. Each robotic device operates in a conditionally chosen state depending on its task at the time. A robotic device may operate in the search state if it is looking for a food-like target. Contrary, it would operate in the return state if it has already found the food-like target and is returning to the nest-like point.

Each robotic device's orientation in a conditionally chosen location depends on the trail pheromones level within the environment. An ant-like robotic device must choose one direction to orientate among eight possible directions. They orientate to that one location with a higher trail pheromone level than the other seven locations. As already explained, ant-like robotic devices move after a successful orientation. Trail pheromones are dropped within the environment for communication purposes regarding the nest-like point, food-like target, and obstacle location. Each robotic device reads and updates the trail pheromone within the environment. Trail pheromones evaporate from the environment when no ant-like robotic devices are updating them. Trail pheromone diffuses when dropped within the environment. Figure 3.7 visualises the relationship between entities and data.

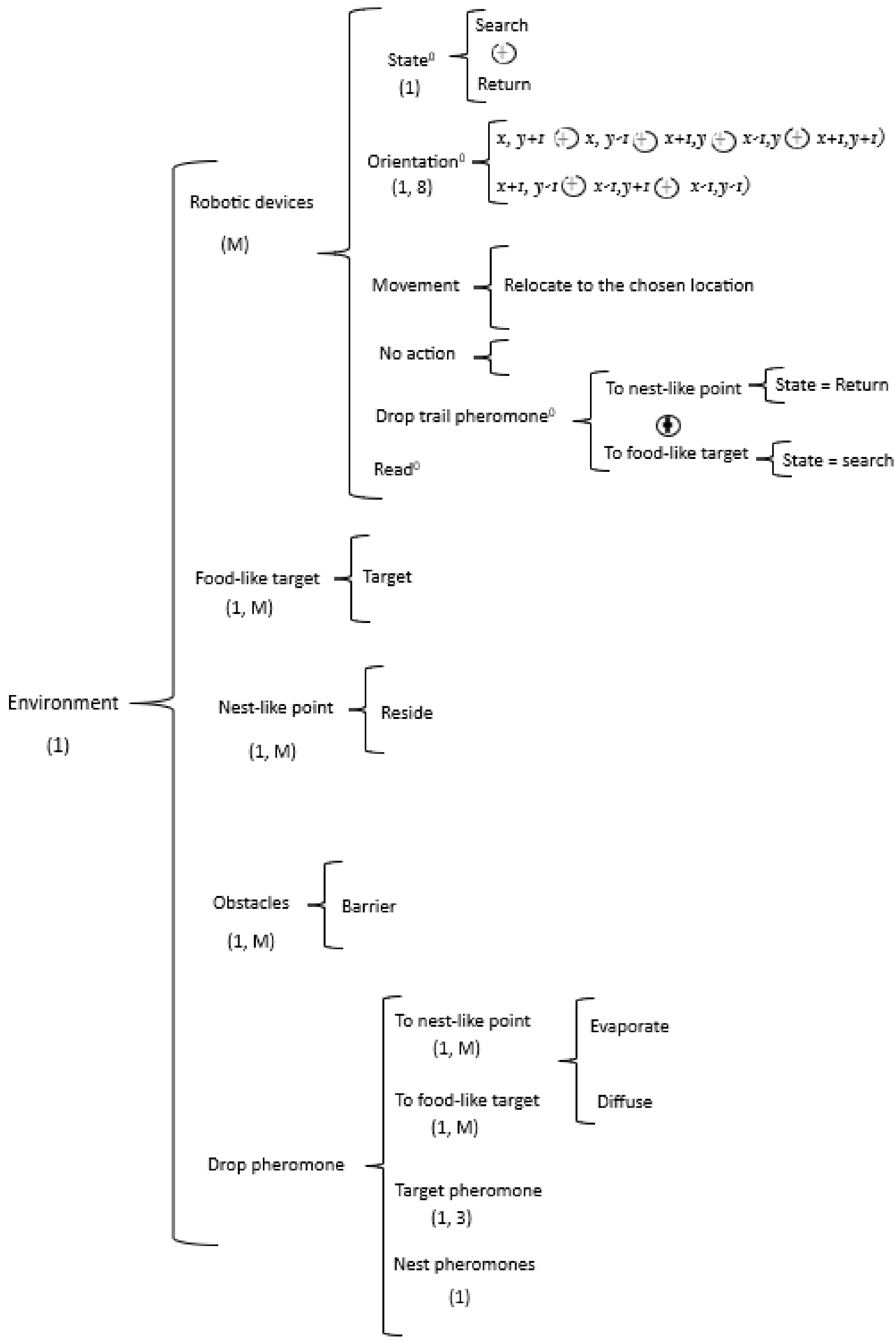

Figure 3.7 Warnier Orr Diagram

3.8 Physical design

In this study, physical design refers to the transformation of the logical designs into the physical system diagram. Precisely, this section combines the Warnier-Orr Diagram, Entity-Relationship Diagram, and the Data Flow Diagram presented in the previous section into the proposed ants-inspired ontology. The ants-inspired ontology is the formal knowledge representation model this study seeks to deliver in the body of knowledge.

3.8.1 Ontology

The ontology diagram is divided into two levels; level 0, and level 1. The level 0 diagram summarises the entire ants-inspired ontology, while the level 1 diagram provides more ontology details.

An ontology, in the context of the proposed designs, captures the entities of ant systems and their relationships. It captures the data insinuated to flow within ants-systems, as well as captures the hierarchical component between the entities and the data thereto. It combines the logical designs into a formal knowledge representation model, giving more detailed elaborations of how the different key components work together. Figure 3.8 and 3.9 depicts the proposed ontology, which is the key deliverable of this study.

In this design, the environment is the central aspect of the ontology as inherited from the logical Warnier Orr design. It is surrounded by the components that have been insinuated to prevail at the next level before we dwell on the level of the nitty gritty. The components are ant-like robotic devices and objects. The ant-like robotic devices consist of the primitive actions identified in Chapter 2. The objects consist of the entities within the environment. The ant-like robotic devices show a significant relationship with the objects. The object consists of the trail pheromone, which triggers the robotic devices to determine the switching between internal states, orientate to choose a direction stochastically, and move from one location to another. The robotic device is aware of what to do next after reading the environment. The ontology is then tested for its effectiveness on path finding and path following behaviour. The experiments focus on determining the speed, visual emergence behaviour, and resource demand. The next chapter evaluates the effectiveness of our proposed ontology.

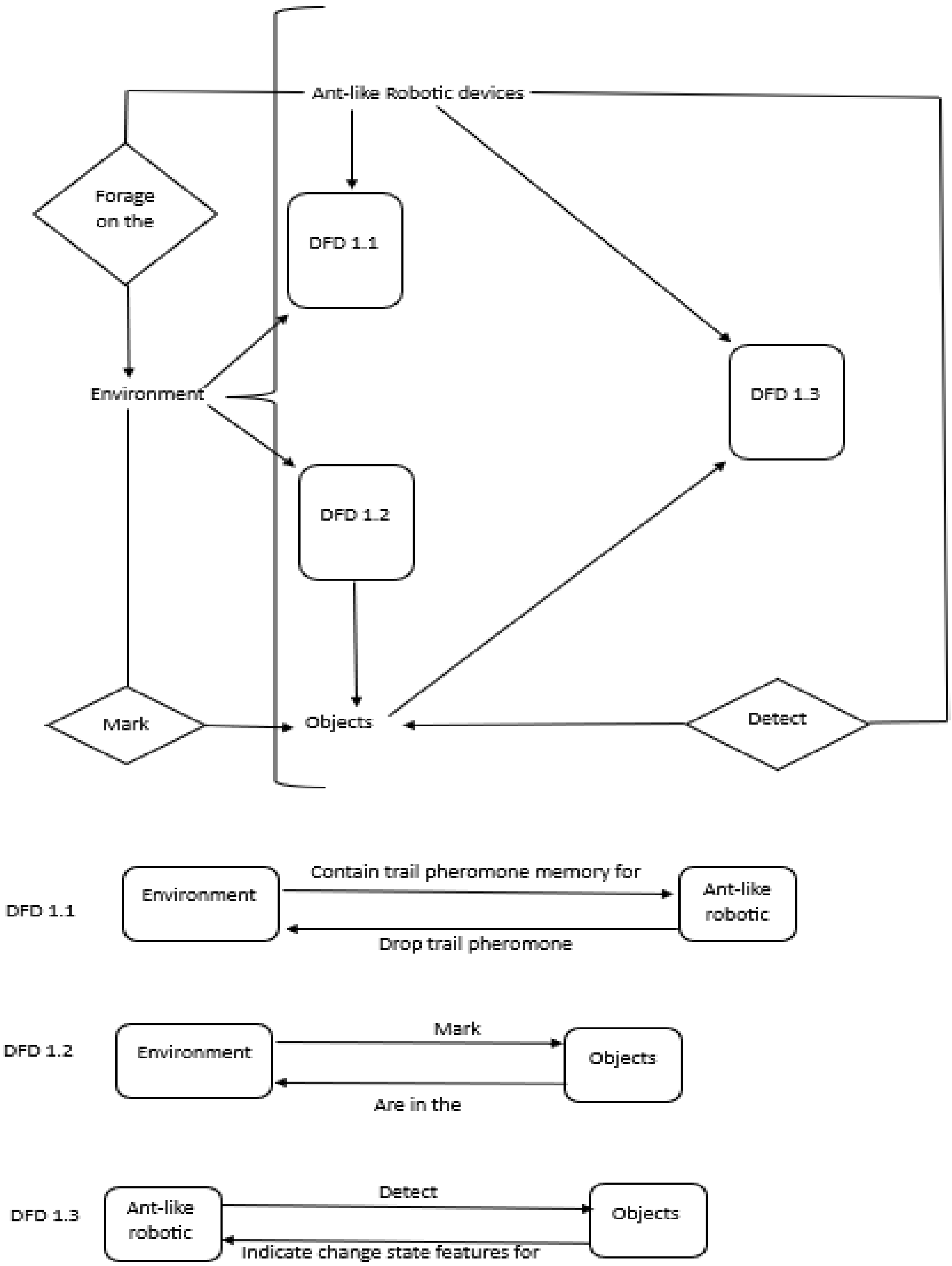

Figure 3.8 Level 0 of the ontology

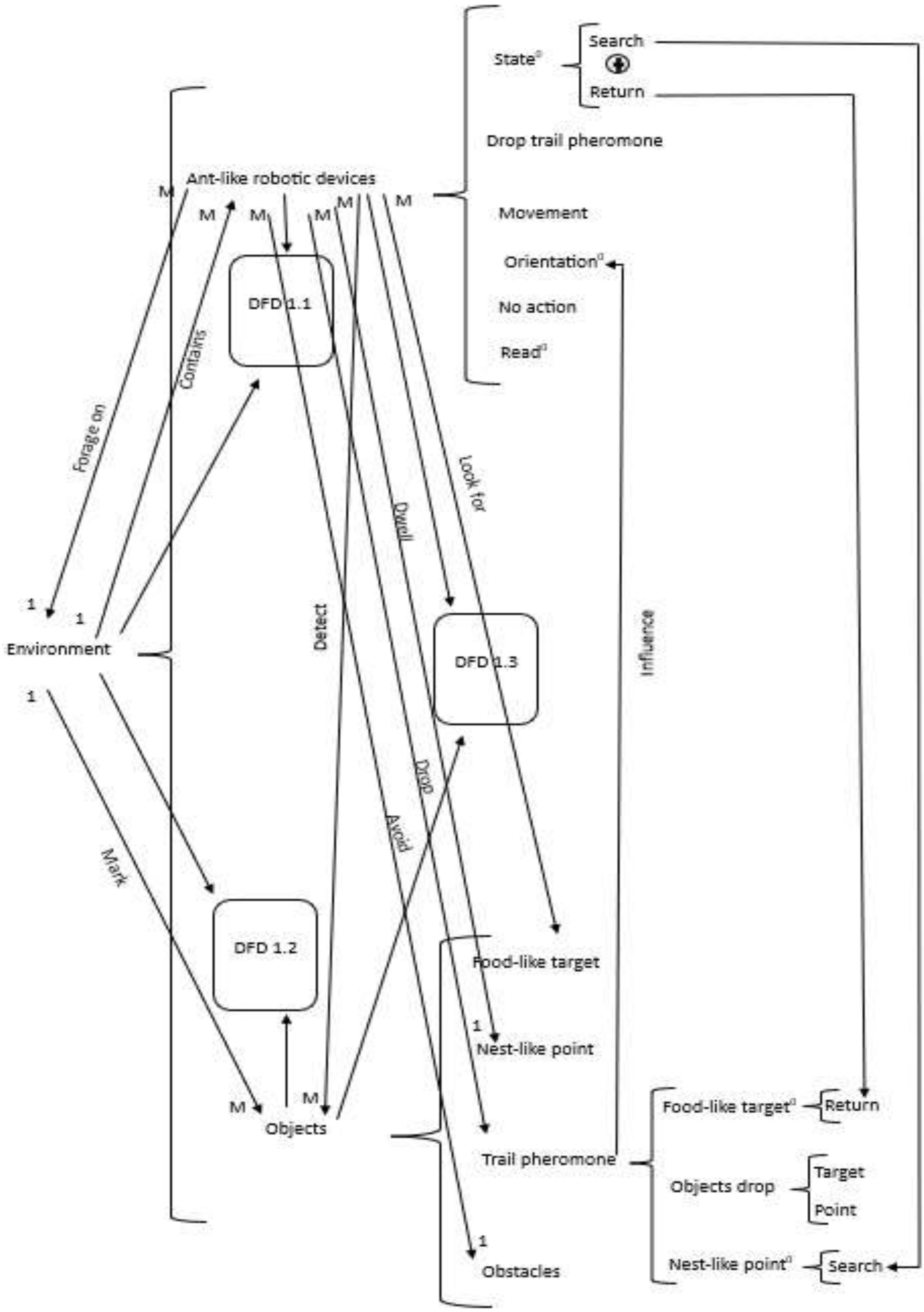

Figure 3.9 Level 1 of the ontology

3.8.2 Ontology Evaluation

Evaluation of the effectiveness of the proposed ants-inspired ontology involves assessing the visual plausibility of the emergent behaviour depicted by robotic devices deployed in the selected environment to complete deterministic tasks. It also involves an assessment of the speed of emergence, as well as the general resource demand for running the simulation model. In this context, the visual plausibility of the emergent behaviour observed refers to the observation and exhibition of the path finding and path following behaviour. We sought to visually validate the ability of the robotic devices in the swarm to effectively form trodden paths between the nest-like points and the food-like targets. We sought to visually confirm collaboration and collective behaviour emanating from the interactions among the member robotic devices of the swarm.

Speed of emergence evaluates the average duration it takes robotic devices to travel round trips from the nest-like point to the food-like targets, and return to the nest-like point. In this case, time or duration was measured in computational iterations to avoid the bias that may arise from the technical specifications of different Computer Systems used. The lower number of iterations are desirable, indicating less time to complete the task at hand. The higher number of iterations indicates long delayed trips.

We then talk of resource demand to indicate the number of computational resources the model would require to effectively run. These resources include the CPU time required, as well as RAM usage. The study showed that the proposed ants-inspired ontology is CPU time and RAM usage wise.

3.8.3 Data collection

The data collected were the visual performance, speed of emergence, as well as resource demands. Visual performances were observed over replicated simulations, while speed of emergence was a centrally placed view from 15 repeated simulations. Visualised emergent behaviour is shown as screenshots. Resource demand and speed are tabulated as shown in Tables 3.1 and 3.2.

Table 3.1 Speed record

Replicated Experiment	Time in seconds		
	Speed to Target 1	Speed to Target 2	Speed to Target 3
1	….	….	….
:	:	:	:
15	….	….	….

Table 3.2 Resource Demand Record

Replicated Experiment	Metrics	
	CPU time	RAM usage (MB)
1	….	….
:	:	:
15	….	….

3.8.4 Data management

This study ensured that all the data collected was used for research purposes only. Nothing was done with the collected data to violate or infringe the rights of the data. The data was analysed before the experiment began to ensure that the data were well managed and preserved in the future. We consideried many aspects of data management, such as storage, security, backup, and access to the data. Our data were stored in the student and supervisor's laptops. We backed up our data in iCloud to avoid loss or damage. We managed data security by setting a password for our data files. The data files would only be accessed by the student and the supervisors. The data would be monitored daily for safety purposes. The data would only be shared when necessary, and only via Sol Plaatje University emails.

3.8.5 Data analysis

The key analysis was the extraction of central tendencies, variability, correlations, and inferential statistics. Central tendencies (mean, mode, and medium) indicate where the distribution centre is. Our reason for finding central tendencies was to gather information about the shape and nature of the distribution resulting from the data collected. However, variabilities (Kurtosis, skewness, and standard deviation) measure the degree to which data points in a statistical distribution deviate from the centre of mass. Associations and relationships between variables were found through correlation analyses before determining how confident we could reach conclusions through inferential statistics (T and F-tests).

3.9 Summary of the chapter

This chapter explained the methodology and theoretical underpinnings that underpinned this study. The statement of the problem addressed in Chapter 1 was driven by some background information on design science research presented in the chapter's introduction. The theoretical foundation for this research was extensively examined after that. The positivist school of thought was reflected in the theoretical framework that guides our reasoning in design science research, where deductive reasoning was regarded as a means of gathering quantitative data.

The research design focused on the primitive actions identified, and how each could be interpreted in a programming language. The system modelling was explained and visualized using the NetLogo software. The logical design was also visualised using the Entity Relationship diagram, Date flow diagram, and Warnier Orr diagram. The proposed ants-inspired ontology was presented, which triggered the evaluation techniques. It looked closely at the evaluation techniques we measured, including visual emergent behaviour, resource demand, and simulation speed. The method of data collection and analysis was discussed in more detail. The experimental combination to establish appropriate sequencing was also highlighted. A description of the study's conceptual environment was provided as well.

CHAPTER 4: EXPERIMENTS, RESULTS, AND DISCUSSIONS

4.1 Introduction

The emphasis on hypothesis testing and experimental evidence is an aspect of positivist research that uses deductive reasoning. The procedures for testing hypotheses, the corresponding experiments, the metrics used to make any quantitative measurements, and the results of the experiments, are the primary topics covered in this chapter. We first focus on the experiments and data collection techniques employed to acquire useful data.

The following null hypothesis guided the experiments conducted in this chapter: H_0: The actions identified as primitive to the behaviour of simulated ant-like robotic devices do not have any significant effects on the swarm's path finding emergent behaviour. This null hypothesis is statistically stated as follows: H_0: $\mu_1 = \mu_2$, where μ_1 means that the proposed ants-inspired ontology does not influence the path finding emergent behaviour. However, μ_2 means that the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour.

The alternate hypotheses arise for this experiment. H_1: The actions identified as primitive to the behaviour of simulated ant-like robotic devices cause the path finding emergent behaviour. This is statistically stated as follows: H_1: $\mu_1 < \mu_2$, where μ_1 means that the proposed ants-inspired ontology does not influence the path finding emergent behaviour. However, μ_2 means that the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour.

This study used three experiments to assess the ant-like robotic devices' path finding behaviour. The first experiment evaluated the average duration it takes robotic devices to travel round trips from the nest-like point, to the food-like targets, and back to the nest-like point. In the second experiment, we sought to visually validate the ability of the robotic devices in the swarm to effectively form trodden paths between the nest-like points and the food-like targets. In the third experiment, we sought to determine the resource demand to run the proposed ontology. The main component of the analyses and conclusion was the quantitative information gathered from assessing these experiments.

4.1.1 Statements of the problem

The statement of the problem addressed by this chapter can be re-phrased as an investigation of a formal way to represent the knowledge embodied in ant systems. The aim was to design the ants-inspired ontology and verify the claim that the proposed ants-inspired ontology is correct. We simulated the path finding robotic devices using the proposed ants-inspired ontology to confirm that we understand the ants' language. We evaluated and analysed every aspect of this information to arrive at fundamental conclusions. The study's findings arose from these outcomes.

4.2 Layout of the chapter

The following is how the rest of the chapter is organised: Section 4.3 describes the first experiment, which measures the foraging speed of ant-like robotic devices (Experiments 1A, 1B, and 1C). Section 4.4 describes the second experiment, visualising the ant-like robotic devices' emergent behaviour. The third experiment on resource demand (CPU and RAM) is described in Section 4.5. The chapter closes with a summary of the findings in section 4.6.

4.3 Experiment 1: Evaluation of speed of emergence

In this section, the administration of the first experiment is covered. The first experiment is divided into three experiments; experiments 1A, 1B, and 1C. The experiments are explained in more detail below.

In our experiments, we started by describing the null hypothesis under investigation and its alternative. The experiments key metric was then further specified, focusing on the measurement techniques. The experimental design was discussed, drawing attention to the several connoted variables. The outcome of this experiment was reported. Central tendencies and dispersion measurements were used before concluding the performance of ant-like robotic devices under the path finding and path following behaviour.

4.3.1 Hypothesis

The experiment evaluated the average duration it takes robotic devices to travel round trips from the nest-like point, to the food-like targets, and back to the nest-like point; considering environmental obstacles. The null hypothesis for this experiment stated that H_0: The actions identified as primitive to the behaviour of simulated ant-like robotic devices do not have any significant effects on the swarm's path finding emergent behaviour. To find evidence for or against this null hypothesis, experimental testing of the critical action foraging using ant-like robotic devices was used.

Since the null hypothesis lacks directionality, a new hypothesis is generated. The alternative hypothesis states that H_1: The actions identified as primitive to the behaviour of simulated ant-like robotic devices cause the path finding emergent behaviour. We sought evidence on whether to accept or reject the null hypothesis in favour of the alternative.

The ability to create ants-inspired ontology greatly contributes to the body of knowledge. Our discussions, the piece of code we wrote, and the data we presented, were tangible deliverables that could, one day, be used as literature by other researchers.

4.3.2 Speed as Evaluation Techniques

We indicated that speed is the duration an ant-like robotic device takes to collect each food-like target in the environment and return to the nest-like point. The time is measured in seconds. Simulated ant-like robotic devices are centrally dispatched from the testing environment's area to find a specific food-like target nearby. Three locations in the environment serve as food-like targets. We measured the time an ant-like robotic device takes to leave the nest-like point, collect the food-like target, and return to the nest-like point. We predicted that a food-like target nearby would have less time than one farther away or near an obstruction. Smaller time values were preferred because they indicated that the swarm would finish the task faster. Time is a numerical value that we further statistically evaluated.

4.3.3 Experiment 1A setup

The dependent variable for this experiment was Speed. In scientific research, a dependent variable is tested and evaluated through an experiment. Two crucial independent variables were the placement of the food-like target and the location of the obstacles. An independent variable is one that we alter or adjust in an experiment while keeping an eye on the dependent variable. The remaining variables of the experiment were control. In this case, the controlled variables remain constant whether we repeated or triangulated an experiment.

Three food-like targets are placed in different locations in the environment. An obstacle hid Food-like target 3 (Orange), while the other two food-like targets (target 1 and 2) were in open space. Time in seconds was recorded on each food-like target over 15 repeated runs before an average time measure was computed. Figure 4.1 shows the NetLogo setup.

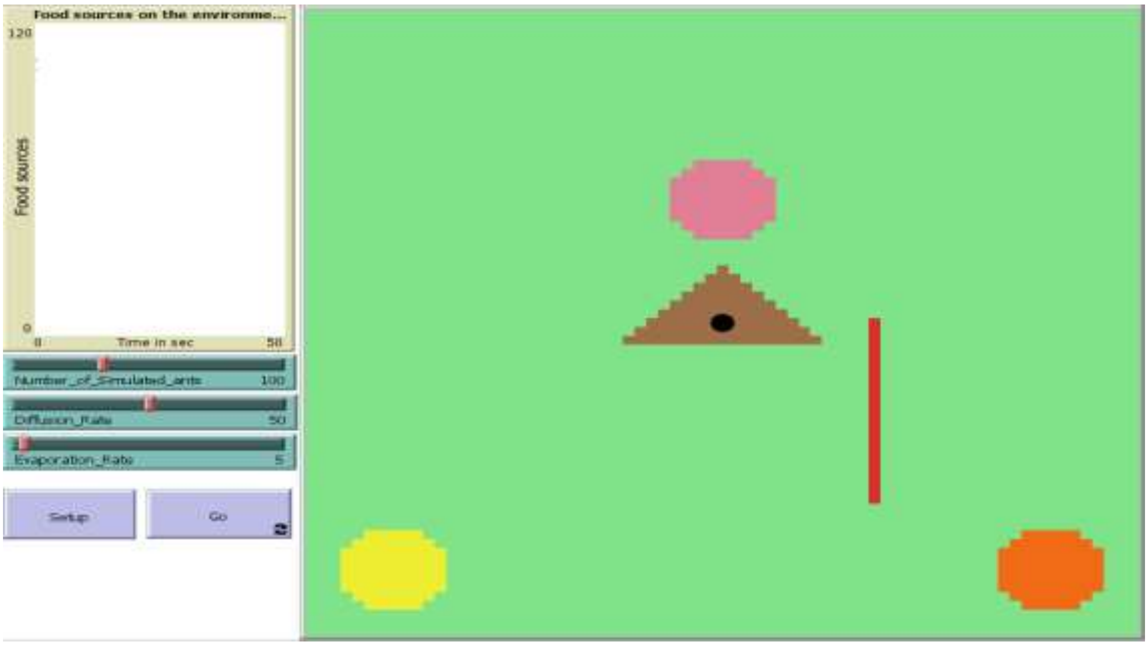

Figure 4.1 Experiment 1A setup

The experiment setup is shown below.

Title: Evaluation of speed of emergence

Null hypothesis: H_0: $\mu_1 = \mu_2$, the proposed ants-inspired ontology does not influence the path finding emergent behaviour.

Alternative hypothesis: H_2: $\mu_1 < \mu_2$, the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour.

Dependent variable: Speed

Independent variable: Locations of the food-like target and Obstacle.

Controlled variable: Number of ant-like robotic devices, Diffusion rate, Evaporation rate, and number of attempts

Procedure: The features of the nest-like point, food-like target, and obstacles are combined to produce an environment. Ant-like robotic devices were set to 100. The diffusion rate was 50, and the evaporation rate was 5. The ant-like robotic devices are depicted from the centre of the environment. The experiment was repeated fifteen times.

Algorithm:

```
to Setup_environment
    Set Ant_like_robotic_devices to 100
    Set Diffusion_rate 50
    Set Evaporation_rate 5
    repeat 15
    [Simulate

      Record]
End
```

Data collection:

Replicated experiment			
	Speed towards target 1	Speed towards target 2	Speed towards target 3
1	….	….	….
:	:	:	:
15	….	….	….

4.3.3.1 Findings

Table 4.1 shows the speed of all the targets collected on each task throughout 15 iterations. One hundred simulated ant-like robotic devices were inputs for the simulation. The target 3 (Orange) had an obstacle, while the remaining targets (1 and 2) were in an open environment. Diffusion and evaporation rates were kept constant in each case.

Table 4.1 Speed measurements

Replicated experiment			
	Speed to target 1	Speed to target 2	Speed to target 3
1	165	514	1146
2	193	550	1174
3	156	1238	816
4	139	433	1079
5	170	520	1400
6	200	490	1310
7	138	449	1119
8	166	521	1152
9	156	706	1348
10	132	844	917
11	169	902	1035
12	156	449	1137
13	156	477	1119
14	174	486	1220
15	156	1257	752

4.3.3.2 Data analysis

We indicated that this study analysed data by extracting central tendencies, variability, correlations, and inferential statistics. Below is a summary of the analyses of the tests for data normality, central tendency, and variability.

4.3.3.2.1 Central tendencies of speed measures

Table 4.2 Central tendencies of speed measures

Food-like target	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
Mean	161.73	655.73	1114,93
Mode	156	449	1119
Median	156	520	1137

Table 4.2 provides a summary of the key trends in reported speed for each category of food-like target. In this section, we calculated the mean, mode, and median speed measurements for each collected food-like target. Target 1 (Pink) was collected first as it was too close to the nest-like point, and the low mean confirmed it. Target 2 (Yellow) was collected second as it did not have an obstacle around it, and the mean confirmed it. Target 3 (Orange) was collected last as it had an obstacle, and the large mean confirmed it.

4.3.3.2.2 Variability

Table 4.3 Measures of dispersion of the speed

Food-like target	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
Std Dev	18.652	279.071	181.061
Kurtosis	0.472	0.950	0.122
Skewness	0.318	1.455	-0.529

In Table 4.3, the speed ratings for each category of food-like target are compiled. We compute the distributions' skewness, kurtosis, and standard deviation in this case. These distributions were produced from the food-like target in each category. Target 1 (Pink) frequently achieved lower variances, confirming the validity of the suggested central tendency, followed by target 3, and lastly, target 2.

4.3.3.2.3 Normality

The Kolmogorov-Smirnov test compared each case's findings to a normal distribution (based on a calculator online posted at the URL: https://www.statskingdom.com/kolmogorov-smirnov-test-calculator.html). It established whether the claimed speed originated from a population with equal distribution regarding potential generalisations and inferences. Here, speed measurements for each food-like target were applied throughout the 15 trials. The food-like targets were analysed in Figures 4.2, 4.3, and 4.4.

Parameter	Value
P-value	0.657
D	0.1793
Sample size (n)	15
Average (x̄)	161.7333
Median	156
Sample Standard Deviation (S)	18.6527
Sum of Squares	4870.9333
K	0.6943
Skewness	0.472
Skewness Shape	Potentially **Symmetrical** (pval=0.416)
Excess kurtosis	0.3176
Kurtosis Shape	Potentially **Mesokurtic**, normal like tails (pval=0.777)
Outliers	193, 200, 132

Figure 4.2 K – S test on target 1 results.

These results indicated no significant variation from the normal distribution, supported by the large value of p = 0.657. In other words, the data did not depart sufficiently from a normal distribution to be statistically significant. This indicates a significant likelihood of wrongly rejecting a viable hypothesis. There was little magnitude difference between the sample distribution and the normal distribution. The target 2 and 3 results exhibited comparable patterns.

Parameter	Value
P-value	0.08196
D	0.3143
Sample size (n)	15
Average (x̄)	655.7333
Median	520
Sample Standard Deviation (S)	279.071
Sum of Squares	1090328.933
K	1.2172
Skewness	1.4549
Skewness Shape	**Asymmetrical**, right/positive (pval=0.012)
Excess kurtosis	0.9504
Kurtosis Shape	Potentially **Mesokurtic**, normal like tails (pval=0.397)
Outliers	1238, 1257

Figure 4.3 K – S test on the target 2 results.

Parameter	Value
P-value	0.6813
D	0.1756
Sample size (n)	15
Average (x̄)	1114.9333
Median	1137
Sample Standard Deviation (S)	181.0606
Sum of Squares	458960.9333
K	0.6802
Skewness	-0.5294
Skewness Shape	Potentially **Symmetrical** (pval=0.362)
Excess kurtosis	0.1216
Kurtosis Shape	Potentially **Mesokurtic**, normal like tails (pval=0.914)
Outliers	816, 752

Figure 4.4 K – S test on the target 3 results.

4.3.4 Experiment 1B setup

Three food-like targets were placed in different locations. An obstacle hid target 2 (Yellow), while the other two targets (1 and 3) were left visible. Time was recorded in seconds on each food-like target over 15 repeated runs, before an average time measure was computed. Figure 4.5 shows the NetLogo setup.

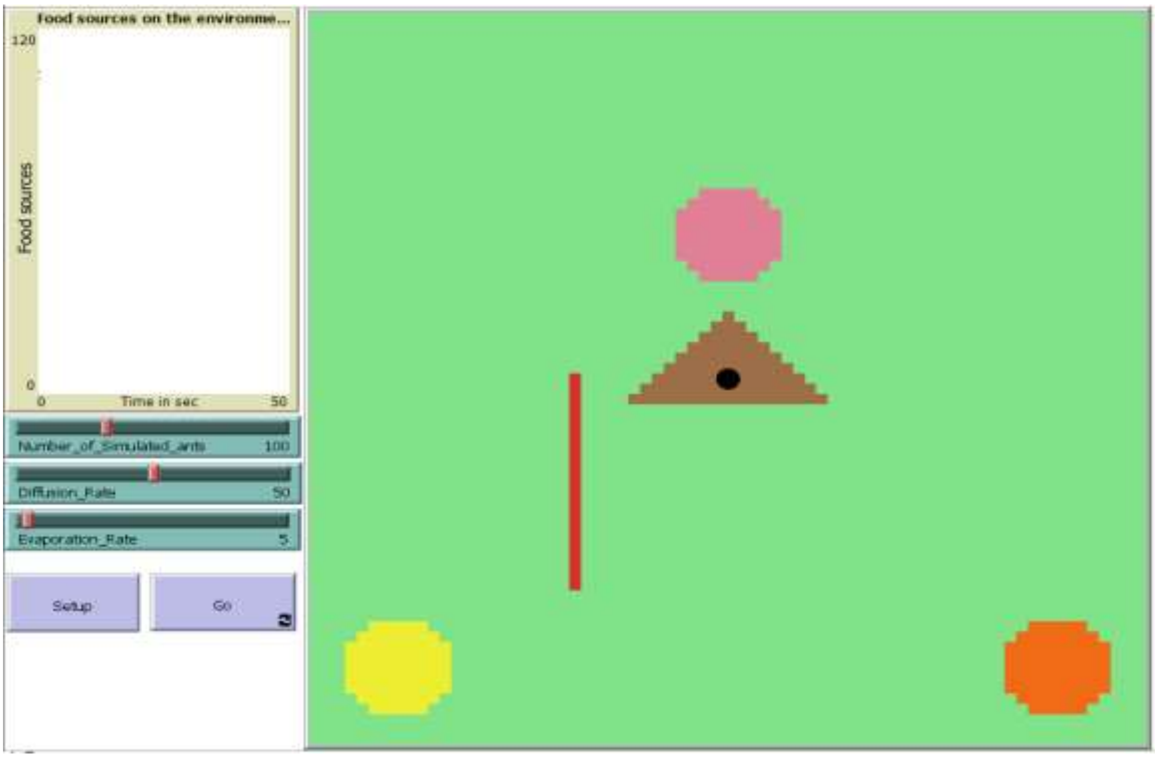

Figure 4.5 Experiment 1B setup

The experiment setup is shown below.

Title: Evaluation of speed of emergence

Null hypothesis: H_0: $\mu_1 = \mu_2$, the proposed ants-inspired ontology does not influence the path finding emergent behaviour.

Alternative hypothesis: H_2: $\mu_1 < \mu_2$, the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour.

Dependent variable: Speed

Independent variable: Locations of the food-like target and Obstacle.

Controlled variable: Number of ant-like robotic devices, diffusion rate, evaporation rate, and number of attempts

Procedure: The features of the nest-like point, food-like target, and obstacles were combined to produce an environment. Ant-like robotic devices were set to 100. The diffusion rate was 50, and the evaporation rate was 5. The ant-like robotic devices were depicted from the centre of the environment. The experiment was repeated fifteen times.

Algorithm:

```
to  Setup_environment
    Set Ant_like_robotic_devices 100
    Set Diffusion_rate 50
    Set Evaporation_rate 5
       repeat 15 [ Simulate
                   Record]
End
```

Data collection:

Replicated experiment			
	Speed towards target 1	Speed towards target 2	Speed towards target 3
1	….	….	….
:	:	:	:
15	….	….	….

4.3.4.1 Findings

Table 4.4 shows the speed of food-like target collection for each task throughout 15 iterations. One hundred simulated ant-like robotic devices were inputs for the simulation. The target 2 (Yellow) had an obstacle, while the remaining targets (1 and 3) were in an open environment. Diffusion and evaporation rates were kept constant in each case. Table 4.4 Speed measurements

Replicated experiment			
	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
1	147	1229	468
2	165	1237	835
3	156	1367	734
4	156	1339	743
5	160	1370	660
6	156	1376	715
7	170	1460	710
8	160	1420	910
9	156	1335	761
10	174	1133	449
11	147	1192	449
12	156	1146	761
13	130	1700	650
14	200	1490	490
15	174	1192	486

4.3.4.2 Data analysis

We indicated that this study analysed data by extracting central tendencies, variability, correlations, and inferential statistics. Below is a summary of the analyses of the tests for data normality, central tendency, and variability.

4.3.4.2.1 Central tendencies of speed measures

Table 4.5 Central tendencies of speed measures

Food-like target	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
Mean	160.467	1332.4	654.733
Mode	156	1192	761
Median	156	1339	710

Table 4.5 provides a summary of the key trends in reported speed for each category of food-like target. In this section, we calculated each collected food-like target mean, mode, and median speed measurements. Target 1 (Pink) was collected first as it was too close to the nest-like point and supported by the low mean. Target 3 (Orange) was collected second as it did not have an obstacle around it, and the average mean confirmed it. Target 2 (Yellow) was collected last as it had an obstacle, and a large mean confirmed it among the other food-like targets.

4.3.4.2.2 Variability

Table 4.6 Measures of dispersion of the speed

Food-like target	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
StdDev	16.656	151.706	150.281
Kurtosis	2.536	0.996	-1.178
Skewness	0.732	0.817	-0.164

In Table 4.6, the speed ratings for each category of food-like targets are compiled. We computed the distributions' skewness, kurtosis, and standard deviation in this case. These distributions were produced from the food-like target in each category. Target 1 (Pink) frequently achieved lower variances, confirming the validity of the suggested central tendency, followed by target 3 (Orange) and lastly, Target 2 (Yellow).

4.3.4.2.4 Normality

The Kolmogorov-Smirnov test compared each case's findings to a normal distribution (based on a calculator online posted at the URL: https://www.statskingdom.com/kolmogorov-smirnov-test-calculator.html). It established whether the claimed speed originates from a population with equal distribution regarding potential generalisations and inferences. Here, speed measurements for each food-like target were applied throughout the 15 trials. The food-like targets are analysed in Figures 4.6, 4.7, and 4.8.

Parameter	Value
P-value	0.6012
D	0.1877
Sample size (n)	15
Average (x̄)	160.4667
Median	156
Sample Standard Deviation (S)	15.6564
Sum of Squares	3431.7333
K	0.727
Skewness	0.7322
Skewness Shape	Potentially **Symmetrical** (pval=0.207)
Excess kurtosis	2.5363
Kurtosis Shape	**Leptokurtic**, positive kurtosis, long **heavy tails** (pval=0.024)
Outliers	130, 200

Figure 4.6 K – S test on the Target 1 results.

Parameter	Value
P-value	0.9135
D	0.1353
Sample size (n)	15
Average (x̄)	1332.4
Median	1339
Sample Standard Deviation (S)	151.7064
Sum of Squares	322207.6
K	0.5239
Skewness	0.8168
Skewness Shape	Potentially **Symmetrical** (pval=0.159)
Excess kurtosis	0.9963
Kurtosis Shape	Potentially **Mesokurtic**, normal like tails (pval=0.374)
Outliers	1700

Figure 4.7 K – S test target 2 results.

Parameter	Value
P-value	0.5419
D	0.1968
Sample size (n)	15
Average (x̄)	654.7333
Median	710
Sample Standard Deviation (S)	150.2814
Sum of Squares	316182.9333
K	0.7623
Skewness	-0.1636
Skewness Shape	Potentially **Symmetrical** (pval=0.778)
Excess kurtosis	-1.1784
Kurtosis Shape	Potentially **Mesokurtic**, normal like tails (pval=0.293)
Outliers	

Figure 4.8 K – S test on the target 3 results.

These results indicate no significant variation from the normal distribution, supported by the large value of $p = 0.6012$. In other words, the data did not depart sufficiently from a normal distribution to be statistically significant. This indicates a significant likelihood of wrongly rejecting a viable hypothesis. As a result, there was little magnitude difference between the sample distribution and the normal distribution. The target 2 and 3 results can exhibit comparable patterns.

4.3.5 Experiment 1C setup

Three food-like targets were placed in different locations in the environment. An obstacle hid target 1 (Pink), while the other two food-like targets (2 and 3) were left in open space. Time was recorded in seconds on each food-like target over 15 repeated runs, before an average time measure was computed. Figure 4.9 shows the NetLogo setup.

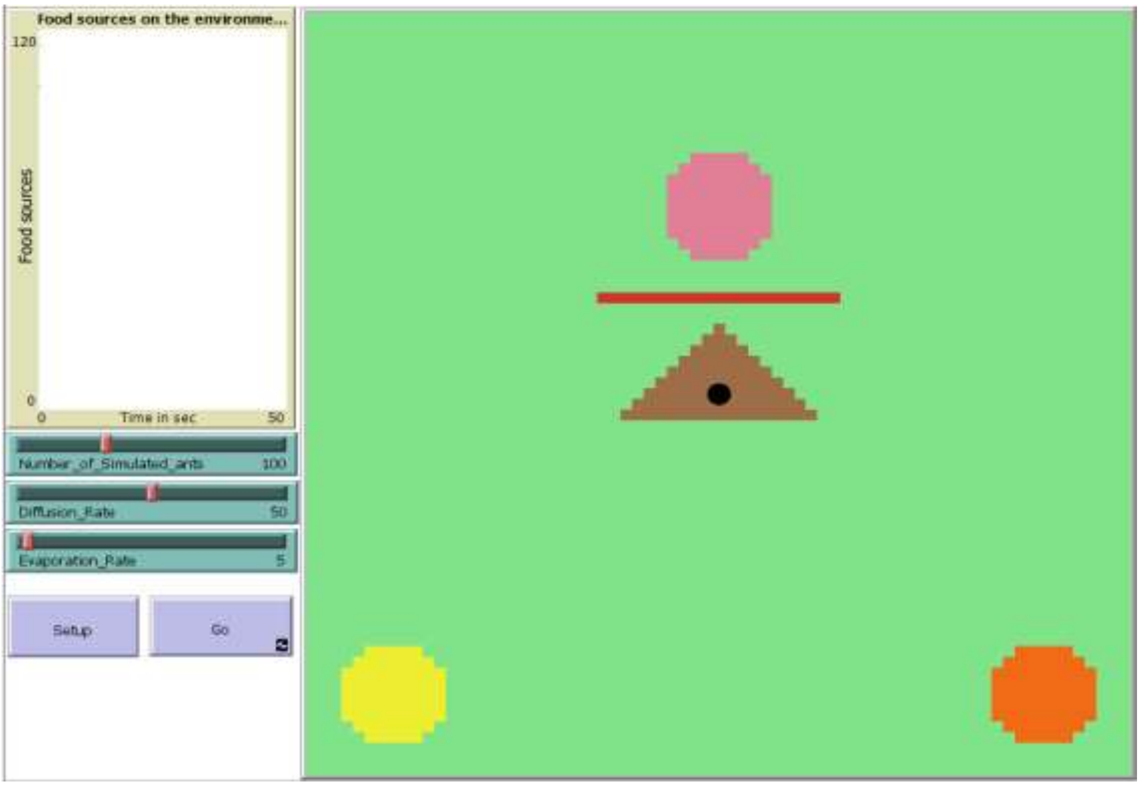

Figure 4.9 Experiment 1C setup

The experiment setup is shown below.

Title: Evaluation of speed of emergence

Null hypothesis: H_0: $\mu_1 = \mu_2$, the proposed ants-inspired ontology does not influence the path finding emergent behaviour.

Alternative hypothesis: H_2: $\mu_1 < \mu_2$, the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour.

Dependent variable: Speed

Independent variable: Locations of the food-like target and Obstacle.

Controlled variable: Number of ant-like robotic devices, Diffusion rate, Evaporation rate, and number of attempts

Procedure: The features of the nest-like point, food-like target, and obstacles were combined to produce an environment. Ant-like robotic devices were set to 100. The diffusion rate is 50, and the evaporation rate was 5. The ant-like robotic devices were depicted from the centre of the environment. The experiment was repeated fifteen times.

Algorithm:

```
to   Setup_environment
     Set Ant_like_robotic_devices 100
     Set Diffusion_rate 50
     Set Evaporation_rate 5
        repeat 15 [ Simulate
                    Record]
End
```

Data collection:

Replicated experiment			
	Speed to target 1	Speed to target 2	Speed to target 3
1	….	….	….
:	:	:	:
15	….	….	….

4.3.5.1 Findings

Table 4.7 shows the speed of food-like target collection for each task throughout 15 iterations of the foraging. One hundred simulated ant-like robotic devices were inputs for the simulation. The target 1 (Pink) had an obstacle, while the remaining targets (2 and 3) were in an open environment. Diffusion and evaporation rates were kept constant in each case.

Table 4.7 Speed measurements

Replicated experiment			
	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
1	1192	1046	394
2	1115	609	704
3	1101	631	602
4	1165	651	486
5	1101	572	521
6	1192	706	550
7	1220	679	504
8	1130	631	653
9	1160	580	572
10	1128	653	561
11	1110	730	650
12	1137	609	633
13	1152	697	565
14	1152	668	520
15	1110	688	638

4.3.5.2 Data analysis

We indicated that this study analysed data by extracting central tendencies, variability, correlations, and inferential statistics. Below is a summary of the analyses of the tests for data normality, central tendency, and variability.

4.3.5.2.1 Central tendencies of speed measures

Table 4.8 Central tendencies of speed measures

Food-like target	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
Mean	1144.333	676.667	570.2
Mode	1192	609	394
Median	1137	653	565

Table 4.8 provides a summary of the key trends in reported speed for each category of food-like target. In this section, we calculated each collected food-like target mean, mode, and median speed measurements. Target 3 (Orange) was collected first as it was not hidden and confirmed by the low mean. Target 2

(Yellow) was collected second and was confirmed by the average mean. Target 1 (Pink) was collected last as it had an obstacle, and the large mean confirmed it. The food-like targets 2 and 3 were assumed to have similar means as they had the same distance to the nest-like point and were both not hidden. The mean supported the assumption by having a slight difference between them.

4.3.5.2.2 Variability

Table 4.9 Measures of dispersion of the speed

Food-like target	Target 1 (Pink)	Target 2 (Yellow)	Target 3 (Orange)
Std Dev	36.10	111.989	79.579
Kurtosis	-0.390	9.417	0.318
Skewness	0.660	2.780	-0.418

In Table 4.9, the speed ratings for each category of food-like targets are compiled. We computed the distributions' skewness, kurtosis, and standard deviation in this case. These distributions were produced from the food-like target in each category. Target 1 (Pink) frequently achieved lower variances, confirming the validity of the suggested central tendency, followed by target 3 (Orange) and lastly, target 2 (Yellow).

4.3.5.2.3 Normality

The Kolmogorov-Smirnov test compares each case's findings to a normal distribution (based on a calculator online posted at the URL: https://www.statskingdom.com/kolmogorov-smirnov-test-calculator.html). It establishes whether the claimed speed originates from a population with equal distribution regarding potential generalisations and inferences. Here, speed measurements for each model are applied throughout the 15 trials. The food-like targets are analysed in Figures 4.10, 4.11, and 4.12.

Parameter	Value
P-value	0.9564
D	0.1231
Sample size (n)	15
Average (x̄)	1144.3333
Median	1137
Sample Standard Deviation (S)	36.4097
Sum of Squares	18559.3333
K	0.4768
Skewness	0.6605

Figure 4.10 K – S test on the Target 1 results.

Parameter	Value
P-value	0.9687
D	0.1183
Sample size (n)	15
Average (x̄)	570.2
Median	565
Sample Standard Deviation (S)	79.5794
Sum of Squares	88660.4
K	0.4583
Skewness	-0.4169

Figure 4.11 K – S test target 2 results.

Parameter	Value
P-value	0.2082
D	0.2634
Sample size (n)	15
Average (x̄)	676.6667
Median	653
Sample Standard Deviation (S)	111.9889
Sum of Squares	175581.3333
K	1.02
Skewness	2.7976

Figure 4.12 K – S test on the target 3 results.

These results indicate no significant variation from the normal distribution, supported by the large value of $p = 0.9564$. In other words, the data did not depart sufficiently from a normal distribution to be statistically significant. This indicates a significant likelihood of wrongly rejecting a viable hypothesis. As a result, there was little magnitude difference between the sample distribution and the normal distribution. The target 2 and 3 results can exhibit comparable patterns.

4.3.6 Discussion

Our objectives were to determine the speed at which each food-like target would be collected, and to compare how long each took depending on whether it was in an open area or near an obstacle. We compared targets 1, 2, and 3. According to our comparison, food-like targets close to a nest-like point had less collection time than those further away or hidden. We considered smaller time values because they implied that the swarm would accomplish the task faster. Central tendencies, variability, and normality were calculated based on each food-like target's results. Generally, the food-like target in an open area and too close to the nest-like point had a shorter collection time than the food-like target far from the nest-like point or close to the nest-like point but hidden by an obstacle. We could not accept the null hypothesis in favour of the outcome that the critical actions of simulated ant-like robotic devices caused path finding emergent behaviour in swarms of ant-like robotic devices.

4.4 Experiment 2: Visual behaviour of ant-like robotic devices

In this experiment, we started by describing the experiment's key metric, which was then further specified, and focused on the measurement techniques. The experiment's design was discussed, drawing attention to the several connoted variables. The outcome of this experiment is reported. Figures are used to visualise the emergent behaviour under path finding and path following.

4.4.1 Hypothesis

The experiment focused on visualising the ant-like robotic devices emergent behaviour on path finding and path following behaviour. The null hypothesis for this experiment is stated as H_0: The actions identified as primitive to the behaviour of simulated ant-like robotic devices do not have any significant effects to the swarm's path finding emergent behaviour. To find evidence for or against this null hypothesis, experimental testing of the critical action on path finding and path following behaviour was simulated.

Since the null hypothesis lacks directionality, a new hypothesis was generated. The alternative hypothesis states that H_1: The actions identified as primitive to the behaviour of simulated ant-like robotic devices cause the path finding emergent behaviour. We sought evidence on whether we accept or reject the null hypothesis in favour of the alternative.

4.4.2 Visual Emergent Behavior as Evaluation Techniques

Visual emergent behaviour refers to the group behaviour of simulated ant-like robotic devices that arises from interactions with one another and visual perception of their environment. These actions frequently result from simple rules being obeyed by individual ant-like robotic devices, which then cause complex and well-organised group behaviours. We assessed the emergent behaviour on key aspects such as trail pheromone, switching states, path finding, and assembly. The simulated ant-like robotic devices were utilised similar to foraging for food-like targets, to examine emergent behaviour. For each important aspect, the emergent behaviour was collected from the environment with the use of screen shots. In this case, we assumed that simulated ant-like robotic devices can navigate obstacles, determine the shortest path, and communicate with one another by leaving a trail pheromone in the environment. The results are further examined.

4.4.3 Experimental 2 setup

Three food-like targets were placed in different locations in the environment. An obstacle hid target 3 (Orange), while the other two targets (1 and 2) were in open space. This experiment was repeated 15 times. Setup of the experiment was as follows:

Title: Evaluation of visual emergent behaviour

Null hypothesis: H_0: $\mu_1 = \mu_2$, the proposed ants-inspired ontology does not influence the path finding emergent behaviour.

Alternative hypothesis: H_2: $\mu_1 < \mu_2$, the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour.

Dependent variable: Visual emergent behaviour

Independent variable: Locations of the food-like target and obstacle.

Controlled variable: Number of ant-like robotic devices, diffusion rate, evaporation rate, and number of attempts

Procedure: The features of the nest-like point, food-like target, and obstacles were combined to produce an environment. Ant-like robotic devices were set to 100. The diffusion rate was 50, and the evaporation rate was 5. The ant-like robotic devices were depicted from the centre of the environment. The experiment was repeated fifteen times.

Algorithm:

```
to  Setup_environment
    Set Ant_like_robotic_devices 100
    Set Diffusion_rate 50
    Set Evaporation_rate 5
        repeat 15 [ Simulate
                    Record]
End
```

Data collection: Screen shots of the important aspects of emergent behaviour were the main data collected in this experiment using screen shots.

4.4.4 Findings

The figures below visualise the emergent behaviour of the proposed ants-inspired ontology. The visualisation was taken throughout the experiment during the path finding and path following behaviour. One hundred simulated ant-like robotic devices were inputs for the simulation. The target 3 (Orange) had an obstacle, while the remaining targets (1 and 2) were in an open environment. Diffusion and evaporation rates were kept constant in each case.

4.4.4.1 Trail pheromone

Figure 4.14 below shows the simulated ant-like robotic devices dropping off trail pheromone on the environment for communication. The ant-like robotic devices could retrieve the amount of trail pheromone currently held at the ant-like robotic device's location and update the same trail pheromone levels, by topping it up by a certain quantity. The highlighted area on the environment indicates where the trail pheromone was dropped. It also indicates which location of the environment had more trail pheromone. According to the figure below, target 1 (Pink) had more trail pheromone than targets 2 and 3. The reason behind this was that target 1 was too close to the nest-like point, and it was not easy for the trail pheromone to evaporate quickly due to the number of simulated ant-like robotic devices updating the trail pheromone in a short period. The trail pheromone was effective for the ant-like robotic devices to locate food-like targets, find the shortest path to the nest-like point, and navigate the obstacles in the environment.

Figure 4.13 Trail pheromone

4.4.4.2 Switching states

Figure 4.15 below shows simulated ant-like robotic devices foraging for food-like targets on the environment. The ant-like robotic devices were deployed in the seek mode, where each ant-like robotic device was black. The seek mode determines whether the ant-like robotic device is searching for food-like target or returning to the nest-like point. The ant-like robotic devices left the nest-like point with a black colour, which indicates the searching mode. In the searching mode, the ant-like robotic devices were looking for a food-like target on the environment. Whenever it found a food-like target, it switched states and turned colour into blue, indicating returning to the nest-like point mode. Once it arrived at the nest-like point, it dropped off the food-like target and switched its state back to searching mode. This process repeated until the task was completed. After completing the foraging task, all simulated ant-like robotic devices switched states to returning mode and went back to the nest-like point. The returning mode helped them not to get lost whenever searching for food-like targets but could not find them in the environment.

Figure 4.14 Switching states.

4.4.4.3 Pathfinding

Figure 4.16 below shows the simulated ant-like robotic devices searching for the shortest path from the food-like target back to the nest-like point. The ant-like robotic devices could use any path in the environment, but they chose to follow each other as they found the shortest path back to the nest-like point. Some black ant-like robotic devices returned to the food-like target using the other side of the obstacle. This was due to the diffusion rate of the trail pheromone on the obstacle. The trail pheromone diffused on both sides of the obstacle, leading some of the simulated ant-like robotic devices to use the other side back to the food-like target. After collecting food-like targets, all ant-like robotic devices still chose the shortest path back to the nest-like point. Some ant-like robotic devices were not part of the food-like target collection. This was because some ant-like robotic devices did not encounter the dropped trail pheromone on the environment to communicate the food-like target locations.

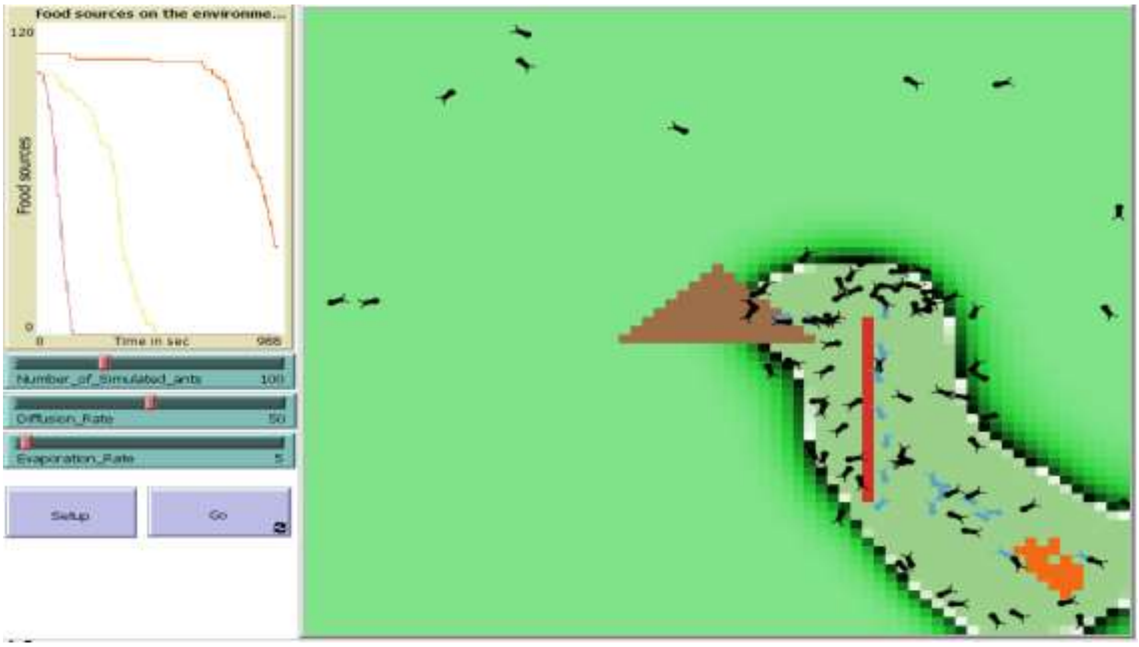

Figure 4.15 Path finding

4.4.4.4 Assembly

Figure 4.17 shows the ant-like robotic devices gathered next to the nest-like point after collecting all the food-like targets on the environment. The ant-like robotic devices returned to the nest-like point after some periods of searching for a food-like target and could not find anything in the environment. Ant-like robotic devices have a time limit to return to the nest-like point after searching for a food-like target in the environment and not finding anything. The ant-like robotic devices had to return to the nest-like point and assemble to decide whether they should continue searching or had collected enough food-like targets for the day. If they chose to continue searching, they chose direction stochastically. Otherwise, they all entered the nest-like point.

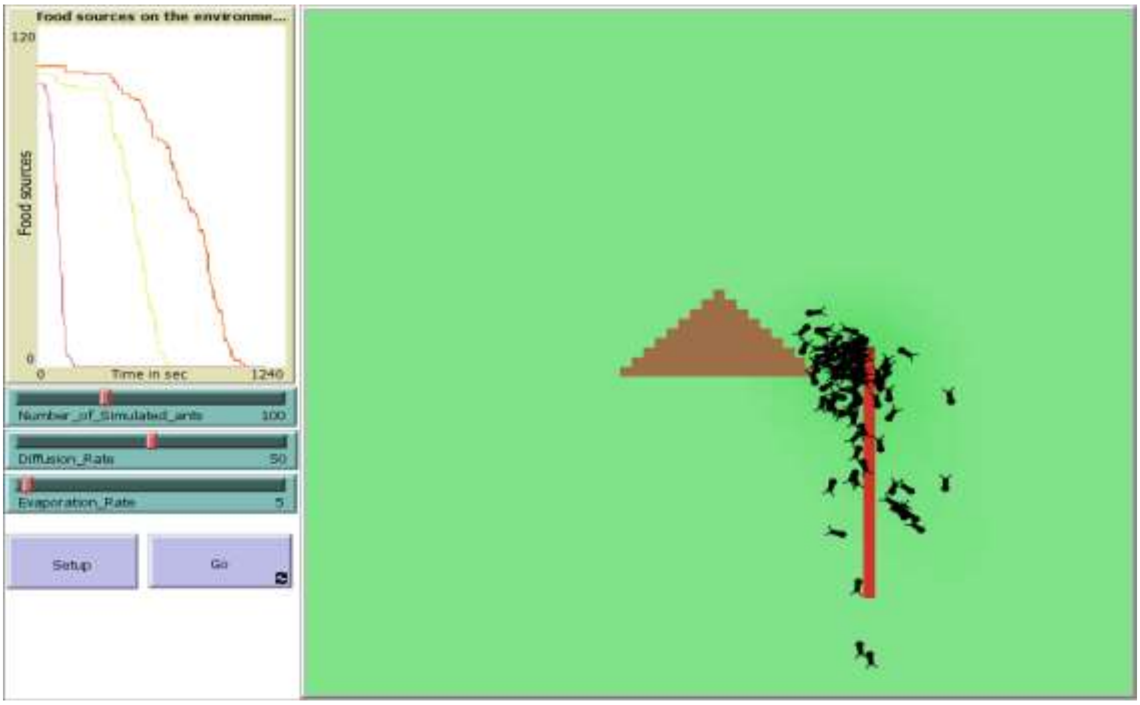

Figure 4.16 Assembly

4.4.5 Discussion

Our objective was to assess the proposed ants-inspired ontology on emergent behaviour. We observed different emergent behaviours based on the experiment conducted. The experiment followed the simple rules of primitive actions identified in the literature review, that were used to design the ants-inspired ontology. The ants-inspired ontology did exactly what the ants in nature do. The ants-inspired ontology also supported what the literature review said early on in Chapter 2. Generally, the ant-like robotic devices could drop off trail pheromone, look for the shortest path around obstacles, collect food-like targets, navigate through obstacles, choose direction stochastically, and switch between states. Based on the results observed in these experiments, we failed to accept the null hypothesis in favour of the outcome of the proposed ants-inspired ontology. The proposed ontology had causal effects on the path finding emergent behaviour observed in swarms of ant-like robotic devices.

4.5 Experiment 3: Evaluation of Resource Demands

This experiment measured the RAM and CPU consumption of the NetLogo software on ant-like robotic devices foraging tasks. The null hypothesis for this experiment was H_0: The actions identified as primitive to the behaviour of simulated ant-like robotic devices did not have any significant effects on the swarm's path finding emergent behaviour. Since the null hypothesis lacked directionality, a new hypothesis was generated. The alternative hypothesis stated that H_1: The actions identified as primitive to the behaviour of simulated ant-like robotic devices cause the path finding emergent behaviour. We sought evidence to accept or reject the null hypothesis in favour of the alternative hypothesis.

4.5.1 Resource Demand as Evaluation Techniques

Resource Demand refers to the expensive machine time required to run the software, such as CPU and RAM usage. This metric determines how much CPU and RAM usage are needed to run the model. Smaller numbers indicate less expensive machine time, hence less demand. This measurement was subjected to statistical analysis.

4.5.2 Experiment 3 setup

Title: Evaluation of the Resources Demands

Null hypothesis: H_0: $\mu_1 = \mu_2$, the proposed ants-inspired ontology does not influence the path finding emergent behaviour.

Alternative hypothesis: H_2: $\mu_1 < \mu_2$, the proposed ants-inspired ontology possesses causal properties to the path finding emergent behaviour.

Dependent variables: CPU and RAM usage.

Independent variable: Replicated iteration

Controlled variable: Number of simulated ants, diffusion rate, evaporation rate, and number of attempts

Procedure: The iteration was repeated fifteen times, where CPU and RAM usage were recorded. The data was collected after each completed run. Ant-like robotic devices were set to 100, the diffusion rate was 50, and the evaporation rate was 5.

Algorithm:

```
to  Setup_environment
    Set Ant_like_robotic_devices 100
    Set Diffusion_rate 50
    Set Evaporation_rate 5
        repeat 15 [ Simulate
                    Record]
End
```

Data collection:

Replicated experiment	Metrics	
	CPU Time	RAM usage (MB)
1	….	….
:	:	:
15	….	….

4.5.3 Findings

Table 4.10 shows the resource demand collected for each task throughout 15 iterations of the foraging task. In each iteration, 100 simulated ant-like robotic devices were input into the simulation. Diffusion and evaporation rates were kept constant in each case. Table 4.10 Resource demand

Replicated Iteration	Metrics	
	CPU (Time)	RAM usage (MB)
1	2.8	255.7
2	2.7	257.9
3	2.4	256.8
4	2.5	273.9
5	2.5	277.1
6	2.1	277.3
7	1.7	278.5
8	2.5	262.6
9	1.2	273.9
10	1.7	278.3
11	3.1	271.1
12	3.1	271.1
13	2.8	277.6
14	1.8	285.4
15	2.6	286.7

4.5.4 Data analysis

We indicated that this study analysed data by extracting central tendencies, variability, correlations, and inferential statistics. Below is a summary of the analyses of the tests for data normality, central tendency, and variability.

4.5.4.1 Central tendencies of speed measures

Table 4.11 Central tendencies of resource demand

Metrics	CPU (Time)	RAM usage (MB)
Mean	2.367	272.26
Mode	2.5	273.9
Median	2.5	273.9

Table 4.11 summarises the key trends in reported resource demand for the expensive machine time. In these results, we calculated CPU and RAM usage in terms of mean, mode, and median resource demand. For the system to run efficiently, it only demanded an average of 2.367 CPU time and 272.26 MB of RAM usage. The resources needed to run the simulation were not very expensive machine time. It could run on any Windows 10 computer efficiently.

4.5.4.2 Variability

Table 4.12 Measures of dispersion of the resource demand

Metrics	CPU (Time)	RAM usage (MB)
StdDev	0.56	9.837
Kurtosis	-0.272	-0.700
Skewness	-0.662	-0.516

Table 4.12 compiles the resource demand ratings for CPU and RAM usage categories. In this case, we computed the distributions' skewness, kurtosis, and standard deviation. These distributions were produced from each category. The system frequently achieved lower CPU and RAM demand variances to run the program. This confirms the validity of the suggested central tendency.

4.5.4.3 Normality

The Kolmogorov-Smirnov test compared each case's findings to a normal distribution (based on a calculator online posted at the URL: https://www.statskingdom.com/kolmogorov-smirnov-test-calculator.html). It established whether the claimed resource demand originated from a population with equal distribution regarding potential generalisations and inferences. Here, resource demand measurements for CPU and RAM were applied throughout the 15 trials. The categories were analysed in Figures 4.18 and 4.19.

Parameter	Value
P-value	0.5542
D	0.1949
Sample size (n)	15
Average (x̄)	2.3667
Median	2.5
Sample Standard Deviation (S)	0.5551
Sum of Squares	4.3133
K	0.7549
Skewness	-0.6618

Figure 4.17 K – S test on the CPU results.

Parameter	Value
P-value	0.6098
D	0.1864
Sample size (n)	15
Average (x̄)	272.26
Median	273.9
Sample Standard Deviation (S)	9.8372
Sum of Squares	1354.776
K	0.7219
Skewness	-0.5157

Figure 4.18 K – S Test RAM usage results.

These results indicated no significant variation from the normal distribution, supported by the large value of p = 0.5542. In other words, the data did not depart sufficiently from a normal distribution to be statistically significant. This indicates a significant likelihood of wrongly rejecting a viable hypothesis. As a result, there was little magnitude difference between the sample distribution and the normal distribution. The RAM usage results can exhibit comparable patterns.

4.5.5 Discussion

Our objectives were to determine the resource demand for the system to run efficiently on the proposed ants-inspired ontology. The resource demands were assessed on the CPU and RAM usage. The results proved that the system was not expensive for machine time. The system only needed 2.367 CPU time and 272.26 MB of RAM. According to the average results, the system could run efficiently on any computer with a minimum of 2GB RAM and 2.39 CPU time. The proposed ants-inspired ontology was efficient; CPU and RAM wise. The ants-inspired ontology did not need much time and space to run on the computer. Generally, the time and space demands were not much. The proposed ants-inspired ontology was not expensive to the machine that would consider using it. We failed to accept the null hypothesis in favour of the outcome that the proposed ants-inspired ontology was efficient, time and space-wise, for simulating path finding emergent behaviour in swarms of ant-like robotic devices.

4.6 Summary of the chapter

This chapter conducted three experiments to test the study hypotheses. The first experiment assessed the speed of simulated ant-like robotic devices among targets 1, 2, and 3. We discovered that the closer the food-like target was to the nest-like point, the faster the food-like target was collected. The second experiment examined the emergent behaviour of simulated ant-like robotic devices. We discovered that the proposed ants-inspired ontology produced emergent behaviour. The third experiment assessed the resource demand on CPU and RAM utilisation. We discovered that the system required less RAM and CPU time to run the simulation. For reliability, the presented results were repeated 15 trials in each experiment. The findings were analysed using central tendencies, variability, and normalcy testing. In general, there was insufficient evidence to accept the null hypothesis. Rather, the conclusion was that the suggested ants-inspired ontology worked well.

CHAPTER 5: CONCLUSION

5.1 Introduction

This chapter describes the work completed in this mini dissertation. This chapter contains the responses to the research questions presented in Chapter 1. In this chapter, we also evaluate the research's actual contributions to the body of knowledge, recommendations, and future work; identifying a few broad topics that will probably be the subject of upcoming studies.

5.2 Conclusion

The following are the questions presented in Chapter 1 and the responses we determined in each case:

1. The first question was: What are the primitive actions of simulated ant-like robotic devices that demonstrate causal properties to the path finding and path following emergent behaviour? (See section 2.4 of this document). This question required us to read more of the literature and observe ants in nature to determine the simulated ant-like robotic devices primitive actions. The primitive actions we identified were Trail pheromone, Switching between state, Orientation, Movements, and No action. The primitive actions were explained in more detail in the above-mentioned section.
2. The second question was: How do we interpret the proposed ant actions in computational or algorithmic form? (See section 3.5.2 of this document). This question required us to write a code that interprets each primitive action into a programming language called NetLogo, demonstrating our programming skills. These primitive actions were combined into an algorithmic form to form a complete software program that we utilised to test the effectiveness of the proposed ants-inspired ontology. The code in Appendix C demonstrates the interpretation of the primitive actions, which helped us answer the second question.

3. The third question was: How do we represent the knowledge of ant-like robotic devices for coordinating the path finding emergent behaviour? (See section 3.8.1 of this document). This question required us to collect ant-like robotic device information and illustrate them using the Logical Design. This helped us represent the information in different diagrams, such as the Entity-Relationship diagram, Data flow diagram, and Warnier Orr diagram. The physical design then combined the logical design diagrams to answer the how part of designing the ants-inspired ontology. This helped us in answering the third question.
4. The fourth question was: To what extent does the proposed ants-inspired ontology effectively cause visually appealing path finding emergent behaviour? (See section 4.5 of this document). This question required us to evaluate the ants-inspired ontology for resource demand. The ants-inspired ontology was less time consuming and RAM wise. The proposed ontology did not need much space to run the simulation. The ontology can run effectively on any Windows 10 computer.

5.3 Recommendations of the study

This study proffers five recommendations as follows:

a) Real-world experimentation with physical robotic devices rather than simulations is imperative. This can assist in validating the ants-inspired ontology's efficacy in practical applications.
b) Collaboration with specialists from domains such as biology, computer science, robotics, and engineering is needed to acquire insights and inspiration for future ants-inspired ontology developments.
c) When the ants-inspired ontology is designed for practical applications, the user interfaces that enable users to configure and control the swarm's behaviour should be created.
d) Consider the ethical and safety issues of deploying swarms of robotic devices. Address concerns about safety, security, privacy, and possible consequences in real-world applications.

e) Consider fine-tuning the ants-inspired ontology's parameters if it did not behave as intended in certain instances. This could include altering the trail pheromone, evaporation rate, diffusion rate, the number of simulated ant-like robotic devices in the environment, or other elements that influence emergent behaviour.

5.4 Contributions

This study makes five contributions, which are as follows:

a) This study proposed a formal knowledge representation approach for defining ants-inspired ontology, adding to the body of knowledge.
b) The ideas to formalise knowledge representation in swarm intelligence models are in progress. This is one of several studies aimed at identifying the key knowledge domains of swarm intelligence systems, with an emphasis on ant systems. Although this is a specific situation, it points us in the direction of more general conclusions.
c) Although the emphasis was on developing an ants-inspired ontology for a homogeneous swarm of ant-bots, the work established a foundation for dealing with heterogeneity.
d) The study adds information to the growing body of research on swarm intelligence by illustrating how natural principles can be employed to tackle complicated engineering issues. This can result in more efficient and resilient swarm robotics methods.
e) This study can help researchers develop scalable solutions for large-scale robotic systems. This can be especially useful in cases where many robots are required to move and coordinate in complex surroundings.

5.5 Future Works

This mini dissertation envisions five significant future work:

a) Practical experiments can be considered in future to verify ant-bot knowledge representation.

b) An ants-inspired ontology could be expanded by including relevant elements to cover a broader range of use cases. It must be examined for completeness, optimality, application, and expandability.

c) Collaboration of the ants-inspired ontology with other swarm intelligence ontologies may lead to real-world heterogeneous swarms in the future.

d) It is worthwhile to investigate the extension of the ants-inspired ontology to deal with ambiguous situations, ambiguity, incompleteness, inaccuracy, vagueness, or impreciseness.

e) Examining the swarm's adaptability in unpredictable and varied situations. Implement algorithms that allow the robotic swarm to adapt to changing circumstances such as obstacles, aspect environments, and environmental conditions.

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APPENDIX A – Approval Letter

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Thursday, 20 July 2023

N Shirindi
Student number: 202112339
Masters Degree
School of Natural and Applied Sciences

Research Project:
An Investigation into the Design of An Ants-Inspired Ontology for Coordinating Pathfinding Robotic Devices

Dear N Shirindi

Approval of the above application was granted by the Senate Higher Degrees Committee (SHDC) on 19 July 2023.

The proposal may be submitted to Senate Secretariat, for the attention of Ms N de Vries at nel-mare.devries@spu.ac.za to serve at the Senate Research Ethics Committee (SREC) for ethics clearance.

The remaining SREC meetings for 2023 is scheduled to take place on:

- 3 August 2023 (the deadline for submission is 20 July 2023)
- 10 October 2023 (the deadline for submission is 21 September 2023)

Yours sincerely,

____

Prof D Meyer
Chairperson: Senate Higher Degrees Committee

www.spu.ac.za

APPENDIX B – Ethics Committee

SOL PLAATJE UNIVERSITY

Light from Africa - for Humanity - Lesedi la Afrika - go Batho - Lig uit Afrika - vir die Mensdom

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Private Bag X5008
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Monday, 21 August 2023

N Shirindi
Student number: 202112339
Master of Science in e-Science
School of Natural and Applied Sciences

Dear N Shirindi

Research Project: *An Investigation into the Design of An Ants-Inspired Ontology for Coordinating Pathfinding Robotic Devices*

Approval of the above application for ethics clearance was granted by the Senate Research Ethics Committee (SREC) at its meeting held on 3 August 2023.

Yours sincerely,

Dr Jody P. Cedras
University Registrar

APPENDIX C – NetLogo Code

```
patches-own [
  Pheromones              ;; amount of trail pheromones on this patch
  food                   ;; amount of food on this patch (0, 1, or 2)
  nest?                   ;; true on nest patches, false elsewhere
  nest-scent              ;; number that is higher closer to the nest
  food-source-number      ;; number (1, 2, or 3) to identify the food sources
  obstacle?                   ;; true if there's an obstacle on this patch
  obstacle-scent
]

breed [frame frames]

;;;;;;;;;;;;;;;;;;;;;;;;
;;; Setup procedures ;;;
;;;;;;;;;;;;;;;;;;;;;;;;

to Setup
  clear-all
  set-default-shape turtles "bug"
  create-turtles Number_of_Simulated_ants
  [ set size 2          ;; easier to see
    set color black  ]    ;; red = not carrying food
  setup-patches
  reset-ticks
end

to setup-patches
  ask patches
  [ setup-nest
    setup-food
    setup-obstacle
    recolor-patch
  ]
end

to setup-obstacle   ;; patch procedure
  ;; set obstacle? variable to true for the obstacle, false elsewhere
  set obstacle? (pycor >= -20 and pycor <= 0 and pxcor = 13)
  ;; spread a obstacle-scent over the whole world -- stronger near the obst
  set obstacle-scent 100 - (abs pxcor) - (abs pycor)
end
```

```
to setup-nest  ;; patch procedure
  ;; set nest? variable to true inside the nest, false elsewhere
  ifelse (pycor >= -2 and pycor <= 6 and abs pxcor <= 6 - pycor)
  [ set nest? true ]
  [ set nest? false ]
  ;; spread a nest-scent over the whole world -- stronger near the nest
  set nest-scent 500 - distancexy 0 0
end

to setup-food  ;; patch procedure
  ;; setup food source one on the right
  if (distancexy (0.8 * max-pxcor)(-0.8 * max-pycor)) < 5
  [ set food-source-number 1 ]
  ;; setup food source two on the lower-left
  if (distancexy (-0.8 * max-pxcor) (-0.8 * max-pycor)) < 5
  [ set food-source-number 2 ]
  ;; setup food source three on the upper-left
  if (distancexy (0.0 * max-pxcor) (0.4 * max-pycor)) < 5
  [ set food-source-number 3 ]
  ;; set "food" at sources to either 1 or 2, randomly
  if food-source-number > 0
  [ set food one-of [1 2] ]
end

to recolor-patch  ;; patch procedure
  ;; give color to nest, food sources, and walls
  ifelse nest?
  [ set pcolor brown ]
  [ ifelse obstacle?
    [ set pcolor red ]  ;; Change the color of the wall to brown
    [ ifelse food > 0
      [ if food-source-number = 1 [ set pcolor orange ]
        if food-source-number = 2 [ set pcolor yellow  ]
        if food-source-number = 3 [ set pcolor pink ] ]
      [ ;; scale color to show chemical concentration
        set pcolor 67 - scale-color 0 Pheromones 0.1 5 ] ] ]
end

;;;;;;;;;;;;;;;;;;;;;
;;; Go procedures ;;;
;;;;;;;;;;;;;;;;;;;;;
```

```
to Go  ;; forever button
  ask turtles
  [ if who >= ticks [ stop ] ;; delay initial departure
    ifelse color = black
    [ look-for-food  ]        ;; not carrying food? look for it
    [ return-to-nest ]        ;; carrying food? take it back to nest
    movements
    fd 1 ]
  diffuse Pheromones (Diffusion_Rate / 100)
  ask patches
  [ set Pheromones Pheromones * (100 - Evaporation_Rate) / 100  ;; slowly evaporat
    recolor-patch ]
  tick
end

to return-to-nest  ;; turtle procedure
  ifelse nest?
  [ ;; drop food and head out again
    set color black
    rt 180 ]
  [ set Pheromones Pheromones + 60  ;; drop some chemical
    uphill-nest-scent ]         ;; head toward the greatest value of nest-scent
end

to look-for-food  ;; turtle procedure
  if food > 0
  [ set color sky + 1     ;; pick up food
    set food food - 1        ;; and reduce the food source
    rt 180                   ;; and turn around
    stop ]
  ;; go in the direction where the chemical smell is strongest
  if (Pheromones >= 0.05) and (Pheromones < 2)
  [ uphill-Pheromones ]
end

;; sniff left and right, and go where the strongest smell is
to uphill-Pheromones  ;; turtle procedure
  let scent-ahead Pheromones-scent-at-angle   0
  let scent-right Pheromones-scent-at-angle  45
  let scent-left  Pheromones-scent-at-angle -45
  if (scent-right > scent-ahead) or (scent-left > scent-ahead)
  [ ifelse scent-right > scent-left
    [ rt 45 ]
```

```
to uphill-Pheromones  ;; turtle procedure
  let scent-ahead Pheromones-scent-at-angle   0
  let scent-right Pheromones-scent-at-angle  45
  let scent-left  Pheromones-scent-at-angle -45
  if (scent-right > scent-ahead) or (scent-left > scent-ahead)
  [ ifelse scent-right > scent-left
    [ rt 45 ]
    [ lt 45 ] ]
end

;; sniff left and right, and go where the strongest smell is
to uphill-nest-scent  ;; turtle procedure
  let scent-ahead nest-scent-at-angle   0
  let scent-right nest-scent-at-angle  45
  let scent-left  nest-scent-at-angle -45
  if (scent-right > scent-ahead) or (scent-left > scent-ahead)
  [ ifelse scent-right > scent-left
    [ rt 45 ]
    [ lt 45 ] ]
end

to movements
  let can-movements? true
  rt random 40
  lt random 40
  if not can-move? 1 or intersects-obstacle? 1 [ rt 60]
  if can-movements? and intersects-obstacle? 1 [ rt 60 ]
end

to-report intersects-obstacle? [distances]
  let target-patch patch-ahead distances
  if target-patch = nobody [ report false ]
  report [obstacle?] of target-patch
end

to-report nest-scent-at-angle [angle]
  let p patch-right-and-ahead angle 1
  if p = nobody [ report 0 ]
  report [nest-scent] of p
end

to-report Pheromones-scent-at-angle [angle]
  let p patch-right-and-ahead angle 1
```

```
;; sniff left and right, and go where the strongest smell is
to uphill-nest-scent  ;; turtle procedure
  let scent-ahead nest-scent-at-angle   0
  let scent-right nest-scent-at-angle  45
  let scent-left  nest-scent-at-angle -45
  if (scent-right > scent-ahead) or (scent-left > scent-ahead)
  [ ifelse scent-right > scent-left
    [ rt 45 ]
    [ lt 45 ] ]
end

to movements
  let can-movements? true
  rt random 40
  lt random 40
  if not can-move? 1 or intersects-obstacle? 1 [ rt 60]
  if can-movements? and intersects-obstacle? 1 [ rt 60 ]
end

to-report intersects-obstacle? [distances]
  let target-patch patch-ahead distances
  if target-patch = nobody [ report false ]
  report [obstacle?] of target-patch
end

to-report nest-scent-at-angle [angle]
  let p patch-right-and-ahead angle 1
  if p = nobody [ report 0 ]
  report [nest-scent] of p
end

to-report Pheromones-scent-at-angle [angle]
  let p patch-right-and-ahead angle 1
  if p = nobody [ report 0 ]
  report [Pheromones] of p
end
```

APPENDIX D – Editor Certificate

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16 November 2023

RE: CERTIFICATE OF LANGUAGE EDITING

To whom it may concern

I hereby confirm that I have proofread and edited the following **Mini-Dissertation** using Windows 'Tracking' System to reflect my comments and suggested corrections for the author(s) to action:

AN INVESTIGATION INTO THE DESIGN OF AN ANTS-INSPIRED ONTOLOGY FOR COORDINATING PATHFINDING ROBOTIC DEVICES.

REFERENCE

Author(s):	Shirindi Ntshuxeko
Student No:	202112339
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Although the greatest care was taken in the editing of this document, the final responsibility for the product rests with the author(s).

Sincerely

16.11.2023

SIGNATURE

This certificate confirms the language editing I have done in my personal capacity and not on behalf of SPU