HCC Architecture - Hormonal Communications and Control Architecture

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HCC Architecture – Hormonal Communications and Control Architecture

By

PAUL RICHARD THOMPSON

Thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
IN
ELECTRICAL ENGINEERING

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Date: 2/22/05

Department of Electrical Engineering
HORMONAL COMMUNICATION AND CONTROL (HCC) ARCHITECTURE

By

PAUL THOMPSON

Master of Science in Electrical Engineering

Abstract

This thesis aims to provide a novel framework for a multiagent system implementation. The major feature of the proposed architecture is the introduction of the biological concept of hormones. The hormones are passed via the communication network to convey limited global system state knowledge. The agents’ response to a hormone is interpreted depending on its own local agent state.

The primary focus of this thesis is the development of the particulars of the architecture. Prior work of multiagent systems research is reviewed and studied for contributions. Biological studies of hormones are employed to draw out interaction rules and analyze control mechanisms in a biological organism. The hormonal communication and control architecture is constructed, with major components detailed by flowcharts.

The proposal is tested with two simulations: A minesweeping problem that has been modeled by other models, and an application of the architecture to a hypothetical ant colony. Research on biological ants is presented to suggest the behavior and goals of a model configured to employ the HCC architecture. The model is fleshed out, and the decisions made by considerations to the architecture are explained. The implementation of the simulation programming with the SWARM programming libraries...
for the Objective-C language is discussed. The data from experimental runs are analyzed with attention to global action.
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1 Introduction

1.1 Overview

The field of multiagent systems is a relatively recent offshoot to the area of intelligent systems. One of the first studies of multiagent systems was performed by Walter [1], in which he investigated complexity and behavior in electromechanical tortoises. The tortoises were endowed with a simple stimuli-response behavior triggered by light. Today, the multiagent research field has branched off in multiple areas investigating physical agent control, communication, and system architecture amongst others. This thesis develops a communication architecture which provides limited system state knowledge to agents in a limited communication area. The state knowledge is used as input by the agent control system.

1.2 Rationale

A team of robots can provide redundancy while confronting a task in which human supervision is dangerous or impractical. A single robot may fail with time or become mired in a situation which terminates in an undesired state, thereby failing its mission. Distributing the intelligence necessary to complete the task amongst many different robots may enable the task to be performed in a more reliable, faster, or cheaper than would be possible with a single robot [2]. However, multiagent systems come with their own set of problems. One issue is control. Multiagent systems, by their nature contain more than one robot. The top-level representation of the control architecture is the paramount design decision, it is the first decision a designer must make. The top-level representation must be either centralized or distributed. If the control is to be
centralized, then communication issues will surface. Communication is the least extensible property of multiagent systems. As the number of agents increase, performance will decrease because of bandwidth limitations [3].

Johnson and Bay state that the key to successful use of communication in multiagent systems is refraining from placing overly burdensome requirements on it [3]. The main purpose of this work is to develop a communication and control method that maximizes the information and control content of messages transmitted throughout the multiagent system.

The main role of communication is to synchronize actions, exchange information, and to provide an avenue for interagent negotiation [4]. However, because of the limitations of communication system as previously stated, it is desirable to minimize the need to explicitly communicate. It is possible to significantly reduce the amount of explicit communication required by installing a method of self-organization, further decentralizing the system, or to enable interactions to occur through manipulation of the environment [5]. On the other side of the coin, Arkin and his group compared the results for a multiagent foraging task with and without communication and came to the conclusion that simple communication can enhance performance [6]. In this paper, it is proposed that it is possible to enable a range of possible interpretation to be embedded in a single explicit message, in the form of hormones, to affect a small or large part of the system. The final control decision is done by the agents themselves, relieving the communication architecture of the need to convey decision making information between individual agents.
1.3 Objective

There are hundreds of papers in journals and conference proceedings regarding multiagent systems. Many of them mention the challenges faced by multiagent system architecture designers. Among these challenges are achieving coherence, determining task decomposition, role assignment, and interaction protocols [7]. The proposal presented by the author has the ambitious goal of meeting all four challenges.

In recent history, researchers have found success in exploring the natural world for design ideas. Multiagent systems are no exception. A great majority of the works that adapt nature has taken hints from insect colonies. Nature has spent eons perfecting sensing and effectors systems [8]. It makes sense to take advantage of sensory and control techniques that have been optimized by nature. Hormones in animals are employed to convey information about both the internal and external state of the organism and the collective that it may belong to the components of the body. This paper adopts this idea to enable agents to sense the system state, and to effect changes through other agents by conveying their perception of the system state.

A question that arises when designing multiagent systems is how intelligent individual agents need to be. Intelligence affects the degree of cooperation required of the system. The less intelligent an individual agent is, the less complex a task has to be for the agent to be able to accomplish it. Cooperation from multiple agents which are either homogenous or heterogeneous in their knowledge and skills are required to complete the task [9]. Smith defines cooperation in the sense that no one unit has sufficient intelligence or knowledge to solve a specific problem. The objective of the
proposal set forth in this paper is to provide the means for agents that are not capable of
detecting the necessary system state or doing the task to convey this fact to other agents
that are capable of doing so.

In the conceptualization of the proposal, the control structure is decoupled from
the communication system in the structure of the control architecture. The hormonal
structure serves as an addendum to the underlying control, conveying state information.
The state information is interpreted by the agent and used to effect control decisions.

1.4 Tasks Involved

It is not the intention of the author to tread paths already walked by other researchers. A survey of the literature of multiagent systems focusing on the means of cooperation and its link to communication will be presented. The endocrine network of animals, especially humans will be studied, and the role of hormones defined.

An important caveat to keep in mind is that any new proposal has to be gauged by the improvements it makes on existing technologies. If not properly constructed, multiple-agent systems may actually increase the complexity of a problem rather than simplifying it [7]. Hormonal communication is not applicable for every problem. The boundaries of the problem have to be defined.

An explicit model of the hormonal communication method will be developed. The cost of explicit communication on the network in terms of bandwidth and energy consumption is assumed to be relatively large in any system [4]. It is inefficient for the agent to attempt communicate the totality of the environment that it senses. This paper discusses the partitioning of the environment such that the communication requirements
are reduced. For cooperative tasks in which results are accomplished by emergent behavior, the agents are programmed with 'simple' behaviors that ideally are coupled with other behaviors to create emergent global-level behavior that leads toward the solution of the problem [5].

Wei-Men Shen originated the idea of hormones in that a high-level action triggers a set of lower-level actions and applies it to self-reconfigurable robots [10]. This paper extends the idea to agents that are not physically coupled together.

Several levels of abstraction are involved in the task of communication [11].

- Network level: Ensuring that messages arrive safely and timely
- Language: A basic set of primitives and a standardized format for exchanging those primitives
- Application: Effective use of communication in solving multiagent problems

The proposal can be considered complete only if those conditions are met.

1.5 Contributions

This proposal aims to provide a platform-independent communication and control system to the multiagent literature. At present, the literature survey shows that most of the tasks chosen for simulation are simple tasks such as object transport, janitorial tasks, and so forth. This proposal shows a method that is applicable to more complex situations. Teams of robots that must perform for a long time in the field need to be adaptable to the environment and changes in the mission [12]. This proposal provides a base for in-situ mission adaptability. This paper will also supply another method of
ensuring redundancy in multiagent systems. The optimal solution for task decomposition and assignment to agents with overlapping capabilities is NP-hard [12]. This proposal provides a method of task assignment that is performed in real time and reassignment when the task is complete or the agents are not needed.

1.6 Outline of thesis

The following chapters contain a brief review of the endocrine system, a literature survey of multiagent systems, a problem proposal and simulation, and conclusions.

Chapter 2 presents a brief overview of the endocrine system, focusing on humans. The hormone is defined, and some specialized hormones in the human endocrine system are illustrated. The feedback mechanisms present in the endocrine system are reviewed.

Chapter 3 covers multiagent systems. A multiagent system is defined, the current state of the field is investigated, and the mechanisms of cooperation and communication are explored. Papers that focus on the influence of nature as pertaining to insect societies is discussed.

Chapter 4 puts forward the hormonal communication and control proposal. This chapter illustrates the connection between the hormonal communication and control method to the endocrine system. Features of the proposal are shown to be desirable, according to work covered in the literature survey. Control and stability analysis is done for specific aspects of the proposed system.

Chapter 5 introduces the topic of biological ants and their infrastructure. This sets the stage for the simulation.
Chapter 6 shows an application of the hormonal communication and control method. The rationale of the specific application is discussed. The parameters and the design decisions pertaining to the simulation is covered. The data from the experimental runs of the simulation is analyzed and conclusions drawn.

Chapter 7 concludes the paper with directions for future work.
2 Endocrine System

2.1 Introduction

In 1628, a study by William Harvey showed for the first time that blood actually circulated through the body via the action of the pumping heart [13]. However, it took two more centuries for the discovery that chemicals that affect the body in a profound way travel through the circulatory system. Arnold Adolph Berthold found the first experimental evidence of hormones when he showed in 1849 that castrated roosters were able to develop normal combs and wattles if the testes from another rooster were transplanted into their abdomen [14]. Brown-Séguard proved that the adrenal gland was essential for life shortly after, in 1856 [13]. The term hormone didn’t appear in the literature till 1905 when Starling found that an injection of duodenal mucosa caused the pancreas to secrete an alkaline substance [13].

C. T. Swain wrote an eloquent passage describing the importance of hormones

When individual cells decided to stop going their own separate ways and to join together both anatomically and functionally the multicellular organisms that were formed had to develop some means for their cells to tell one another what was going on and what to do. Unless this was done, there would be no coordination of the activities of the various parts of the organism and its existence would be constantly threatened. In animals, the coordination is provided by the nervous and endocrine systems, working in concert [15].

In the 19th and 20th century, there came a flood of studies showing that

- Hormones can produce effects even on organs that are isolated from the body
- The same hormone can be produced in different parts of the body
Hormones are mostly secreted in glands and are discharged into blood or lymph nodes via ductless or endocrine glands.

It is possible to see hormonal reactions in animals that are connected only by their circulatory systems if only the first one is stressed.

Links between the nervous and endocrine systems enable the endocrine system to be functionally related to internal and external fluxes (all notes from [13]).

2.2 Definitions

There are hundreds of chemical substances that can produce distinct effects on growth, secretion, metabolism, or behavior. A more detailed classification scheme was proposed in 1935 to categorize the activation chemicals of the body [13].

1. Local activators

2. Distance activators
   a. Diffusion activators
   b. Circulatory activators

Local activators are enzymes that control the rate of chemical reactions. Those enzymes are restricted to the cells that produce them. If those enzymes leave the cell and reach the target by diffusion, they are diffusion activators. Circulatory activators are distributed by the circulatory system. Hormones fall in the circulatory activators category.

Starling came up with the moniker hormone because of its Latin roots, which means ‘I arouse’ [13]. The Merriam-Webster dictionary defines a hormone as “a product
of living cells that circulates in body fluids or sap and produces a specific effect on the activity of cells remote from its point of origin; especially: one exerting a stimulatory effect on a cellular activity” [16].

In the 1920s, Cannon showed that hormones participated in stabilizing the internal environment of the body. He introduced the term *homeostasis* to describe the function of psychological process of stabilization [13].

Hormones are commonly divided in two camps, activator hormones encourage certain cell activities, while inhibitor hormones prohibit certain cell activities [17].

### 2.3 Human Endocrine System

This section focuses on the human endocrine system, but many of the statements are applicable to higher-level animals with a functioning circulatory and endocrine system. Insulin was the first hormonal protein to have its structure determined, and it is the most widely studied [13]. Thus, the main focus of this section is the actions of insulin.

Biological organisms can have many different hormones circulating throughout the body and acting simultaneously without directly affecting each other. Each hormone only affects specific target sites – multiple copies of a single hormone can propagate throughout the body, causing different organs and cells to react differently, based on their local receptors, topology, and their state information [10]. Most hormones are present in the circulatory system at all times, in greater or lesser amounts [15]. The quantity of a specific hormone can vary greatly from one endocrine gland to another. The adrenal cortex contains very small quantities of aldosterone, a hormone that has a role in
regulating blood pressure, however, the pancreas contains more than a lethal dose of aldosterone [13].

Insulin is absolutely vital to continued life. It regulates the glucose level in the blood, the main energy source of the body. It is not the only hormone that has been observed to have an effect on the glucose level however. Adrenaline and the adrenocorticotropic hormone (ACTH) have similar effects on glucose levels [13].

Insulin consists of two chains of amino acids linked together. The complete insulin molecule is not essential for the hormone to be functional. Numerous derivatives of insulin have been found to have insulin-like effects [13]. After insulin is released in the blood, it combines with several plasma proteins in order to protect the insulin molecule from insulin-destroying mechanisms on its journey throughout the body until it leaves the blood to bond to the cells upon which it acts [13]. Once active, insulin can:

- Increase the rate of uptake of glucose in muscle tissue, forming glycogen
- Increase the rate of formation of fatty acids and triglycerides in adipose tissues due to increased uptake of glucose by fat cells
- Increase the rate of protein synthesis in various other tissues. This activity can occur independently of glucose (all of above from [13])

In mammals, the energy for the central nervous system is almost entirely supplied by carbohydrates, but the normal carbohydrate intake is erratic, so insulin regulates the storage and dissipation of glucose by the following methods:

- In an emergency, glucose is liberated from glycogen stores
If the absence of carbohydrates continues for a long time, glucose is produced from non-carbohydrate precursors, protein in particular, during a process called glucogenesis. Glucogenesis is not a rapid process, however, it can take several hours before the rate of production is increased (all of above from [13])

The effects of insulin are explained by multiple mechanisms. The following are several of the mechanisms employed by insulin

- Action of insulin on protein metabolism is thought to operate at the gene level
- Glucose uptake by muscle and fat cells is regarded to be an activation of the cell membrane transport system
- Some of insulin’s effects can be attributed to the removal of an inhibitory influence
- Some variants cause a preliminary rise in glucose concentration, this is thought to be the result of action of another hormone (all of above from [13])

In general, the possible mechanisms for hormone operation act by

- Affecting the membrane transport of various substances
- Affecting the activity of genes
- Affecting protein synthesis
- Changing the amount or activity of an enzyme or protein
- Changing the amount or availability of a cofactor
- Acting as a coenzyme
• Exerting an allosteric effect, the hormone binds to one part of an molecule, changing the molecular structure, thus changing its activity

• Simulating or inhibit the formation of hormone mediators (all of above from [15])

2.4 Feedback Mechanisms

Hormones make their effect felt throughout the body due to various means of receptor reaction. The function of hormones is to maintain homeostasis utilizing mechanisms to stabilize temperature, blood pressure, partial pressure of various gases in the blood [13]. The total mix of the hormones present in the circulatory system determines the body response at any instant [15]. In order to ensure the stability of the body, feedback mechanisms are employed to control the levels of the active hormones. This section describes those mechanisms.

2.4.1 General Feedback Mechanisms

The mechanisms include a various mix of open loop and negative feedback closed loop control. Some operate on the active hormones themselves; others operate via reactions to the hormones. One form of open loop control is that some hormones are more active than others, even though they create the same effect [13]. Clegg also describes several methods of how hormonal secretion can be regulated. One of the simplest mechanisms is to have the hormonal level directly proportional to the monitoring variable. The level of insulin in the blood is controlled by the blood glucose levels. The “product of the action of the hormone itself regulates secretory activity” [13]. A more complicated relationship is to have the level of a hormone regulated by the level
of yet another hormone. As a case in point, the pituitary gland regulates the activity of the thyroid, adrenal cortex, and gonads using thropic hormones. The humoral products of those glands may also return to the pituitary gland as negative feedback. Simple feedback schemes are not adequate to meet the needs of the body in a fluctuating external environment. The hormonal output of the body must be varied to adapt to environmental stresses such as fasting, disease, and other stresses. Two major systems serve as the integration between the internal and external environment, the central nervous system and the endocrine glands [13].

2.4.2 Central Nervous System

The central nervous system (CNS) is composed of neurons that serve as an adaptive neural network, accepting input, and composing output. The nerve cell is a fundamental part of the CNS; there are approximately 1x10^6 neuron cells of various types, mostly concentrated in the deep brain matter or the surface of the brain [1]. The simplest means of the interaction between the CNS and the endocrine system is the sympathetic nervous system and its connection to the adrenal medulla. The activity of the adrenal medulla is completely controlled by the sympathetic nervous system [13]. A more significant relationship is via the anterior pituitary, nicknamed the ‘master gland,’ the “conductor of the endocrine orchestra” [13]. The hypothalamus of the brain functions with the anterior pituitary gland as one unit, also controlling appetite, temperature, and thirst [15]. A large part of the activity of the anterior pituitary gland is controlled by the external environment by the way of its link with the hypothalamus, but a small part of the anterior pituitary gland are regulated by the secretory organs under the its control [13].
The controller of the anterior pituitary gland is in the lower part of the hypothalamus called the median eminence. However, higher centers in the brain and hypothalamus influence the median eminence [15].

Clegg also details the means of the hypothalamus influence on the anterior pituitary gland:

- Chemical substances secreted on the pituitary stalk
- Both excitatory and inhibitory signals are sent to the gland
- Elements in the hypothalamus are sensitive to hormones in the circulating blood. They provide the negative feedback inputs for the hypothalamus
- Reactions induced by exposing a hormone on the hypothalamus are much stronger than those if the hormone is exposed to the anterior pituitary gland alone

2.4.3 Negative Feedback Mechanisms

There are several classes of negative feedback mechanisms, as detailed by Swain [15]:

- Classic direct negative feedback
- Indirect negative feedback in which one hormonal secretion simulates another hormonal secretion which inhibits the first one
- Short-circuit feedback in which the activity of hormonal secretion induces the hormonal production to stop

Some induced hormones respond to the absolute amount of the inducing hormone, or the rate of the change in the hormonal level, or both [15]. High concentrations of
certain hormones can also act as anticatalysis [15]. Most hormonal actions, though, are directly related to the amount of the hormone present within a certain range [15]. Some hormones employ the parathormic effect, which the product of the levels of two hormones is constant [13].

Inactivation of hormones is accomplished by their linkage to the activation site, by hormone-hunters in the blood, or in the intestine system. Most, however, are inactivated in the liver where hormones are conjugated with acids to render them biologically inactive. The biologically inactive hormones can then be filtered in the kidney for elimination. Some hormones have a short lifespan. Glucorticoids, for example have a half-life of four minutes after release, ensuring rapid removal of potent hormones [13]. Others can persist in the circulatory systems for hours, as in the process for glucogenesis.
3 Multiagent systems

3.1 Introduction

This chapter introduces multiagent systems, defines some concepts and terms, and then briefly covers the state of the field. Cooperative methods are investigated, along with controller design. This chapter closes with a look at natural multi-agent systems, and what these systems have inspired.

The history of multiagent systems got its start in the mid-1940s when Walter started experimenting with simple machines that incorporated the stimuli-response behavior pattern. In the early 1970s the field of distributed artificial intelligence (DAI) was developed. DAI was mainly concerned with software agents as opposed to physical robots [18]. In the late 1980s, distributed robotics emerged. Prior to that time, researchers concentrated on single-robot systems or distributed problem-solving systems without robotic components [2].

Researchers were attracted to the advantages that multi-robot approach to decision making offered. Having multiple cost-effective robots offers the promise of speed, reliability, extensibility, and the potential for increased tolerance to uncertain data and knowledge [9]. The computing efficiency of the system also is increased as a result of multiple asynchronous processors working toward a shared solution [11]. The system as a whole is more robust because individual failures can be compensated for, leading to unsupervised groups of mobile robots. Breakdowns, within reason, have no effect on the group scheme [19]. From the agent's perspective, the key difference with the multiagent system approach is the knowledge that the environment can be affected by other agents in
addition to the agent itself [20]. The ability to recognize the influence of other agents and to engage in cooperative tasks requires the agent to be able to make the distinction between itself and other agents, which leads to the requirement of self-awareness.

Nearly all work in cooperative robotics began after the introduction of the behavior-based control paradigm, which is rooted in biological inspirations [2]. This opened up the field to examining the social characteristics of insects and animals. Social insects are nature’s example of loosely coupled decentralized control systems. Understanding those systems is essential in order to understand how to control complex systems. Insects are capable of global task completion based on local interaction rules and perception [21].

Multi-agent systems are powerful and flexible, but because of their inherent dynamic topology (in metamorphic robots), and decentralized configuration, there is a need to go beyond traditional control mechanisms [22]. Butler, et al [23] describes the key features required of a robot operating in an unknown environment

- Ability to operate under uncertainty
- Ability to move on an unknown terrain
- Versatility
- Adaptation to multiple tasks

Those considerations leads to a number of questions that must be answered while designing a multi-agent system, as detailed by Arkin [6]

- Communications
  - Is communication necessary for the agents to achieve a task?
If communications is necessary, what type, and what amount?

What is the appropriate protocol?

What are the quantitative gains earned by incorporating communication?

- Social Organization
  
  What is the right number of agents for a task or situation?

  How should the agents be organized relative to each other?

  Is peer or caste-based society more appropriate?

- Task characteristics
  
  What types of tasks benefit the most from cooperation?

  When is a single complex agent preferred over multiple agents?

- Environmental considerations
  
  What is the likelihood of failure of an agent given the social structure and the communication mechanism?

  What mechanism is best suited for highly hazardous environments?

There are various means of categorizing the world of multi-agent systems, but three major considerations are: Communications, heterogeneity/homogeneity, and method of distributing control [20]. Agah, et al [24] divides the whole sphere of multi-agent autonomous systems in categories as shown in (Figure 3-1)
3.2 Definitions

Multiagent systems fall in several configuration categories; Swarm intelligence, metamorphic robots, and individual agents. This section will define those categories, describe cooperation and control terms.

Generally, an agent is defined as an entity with goal, action, and domain knowledge [20]. The physical capabilities of an agent is defined as its autonomous capability, sensory capability, computation, and action [24]. One way of looking at agents is to determine whether if they are atomic, being composed of single individuals, or as an assemblage, in which a group of agents executing the same task in an interwoven fashion can be considered as a cohesive agent [25]. Swarm-based agents are a set of mobile agents, incorporated either physically or in software, which can communicate directly or indirectly while collectively seeking a trajectory for a distributed problem solution. The swarm trajectory is generated by functional collective patterns and spatio-temporal distribution of the agents [26]. Hackwood [27] takes a stricter definition of an agent. He calls them systems of non-intelligent agents that collectively exhibit intelligent
behavior. Metamorphic, or modular self-configurable robots are composed of many homogenous units that can change their overall topology [28].

When agents consciously interact, they are cooperating. However, there is a plethora of definitions for cooperation. Cao [18] lists definitions put forth by others

- “To associate with another or others for mutual, often economic benefit.” [29]
- “Joint collaborative behavior that is directed toward some goal in which there is common interest or reward” [30]
- “A form of interaction, usually based on communication” [31]
- “[Joining] together for doing something that creates a progressive result such as increasing performance or saving time” [32]
- “given some task specified by a designer, a multiple robot system displays cooperative behavior if, due to some underlying mechanism (i.e. the 'mechanism of cooperation') there is an increase in the total utility of the system” [18]

As can be seen above, there are multiple perspectives of cooperation in multiagent systems. However, they all have in common the idea that cooperation provides added utility over singular operation. Often, in performing tasks, there is choice between accomplishing the task singly or cooperatively. Strictly collaborative tasks are those that inherently require cooperation [33].

In designing multiagent systems, the words fault tolerance, adaptivity, and reliability are frequently bandied about. Parker [7] defines fault tolerance as the ability of the agent to respond to individual agent failures outside of itself or failures in
communication. Adaptivity is defined as the ability of the agent to change its behavior in response to a dynamic environment, mission changes, or changes in the team capabilities or makeup in order to improve performance or to minimize degradation. Reliability is a function that differs from fault tolerance in that it tests for the mission success e.g. the task must be accomplished even though there are no individual failures. A decentralized control system is one in which control and data are both logically and/or physically distributed throughout the system [9]. Loosely coupled systems are those in which individual agents spend more time in computation than communication [9].

3.3 State of the Field

Multi-agent systems research is still a nascent field. It has attracted serious research only in the last 20 years. As a result, the boundaries between research areas are still fluid. In his survey of MAS, Arai, et al [2], has identified several broad areas of research: Architecture, task planning capabilities, and control. Within those areas, current research addresses action selection, delegation of authority and control, communication structure, degree of homogeneity, coherence of local actions, and conflict resolution. This section will attempt to cover a small sampling of those research activities.

3.3.1 Swarms

Theraulaz [26] formally defines swarm behavior rules to consist of cycles of stimuli-response-action patterns. The patterned behavior is decoupled from the individual swarm particles; the system path is the collective of individual paths. Employing this viewpoint, Theraulaz states that swarm dynamics is a morphogenetic
process, in which the structure of the system leads the particles to assume a distribution which reflects the solution to the problem.

3.3.2 Metamorphic robots

Metamorphic robots consist of a number of homogenous units which are capable of connecting with other units to create a desired topology, and are able to alter that topology when necessary. An instance of a metamorphic unit is shown in (Figure 3-2)

![Figure 3-2. The schema for a CONRO self-reconfigurable module and four possible connections to neighbor modules][10]

Several researchers are active in this field, namely Shen [10, 17, 22, 34], Kubica [28], Butler [23], Ueyama [35], Grabowski [36], and Brown [37].

Grabowski employs what he calls Millibots which contain a sensor suite which allows a group of millipedes to self-localize using a rubber tread. His implementation of millibots allows for a small degree of heterogeneity by allowing components to be built
atop a base which contains capabilities for communication, locomotion, and interaction with other units.

Shen has worked with several researchers in developing the CONRO robot base which is employed by the robotics research lab at Carnegie-Mellon. In his work, he concentrates on the communication between the units. Because the topology can change dynamically, communication poses a difficult problem. In an early work [34], the system employed an masterless control system, with the requirement that all the local clocks in the units are synchronized. It worked, but it lacks robustness because it employed an open-loop control architecture, and also flexibility because open-loop architectures restrict the level of complexity possible in actions. Shen [10, 22, 34] eventually developed the idea of hormones as a means of enabling an topology-free communication protocol. This idea was also developed by Butler [23]. However, he allows for a more complex communication choices, including broadcasting hormones systemwide, and having each unit keep a continually updated list of its neighbors for point-to-point communications.

3.3.3 Behavior Architectures

The field of distributed robotics did not really hit its stride until the idea of behavior-based control was developed. With the behavior paradigm, the reactions of an agent can be viewed as behaviors in response to the environment according to the agent state. One of the earliest researchers, Brooks, developed a scheme that he called the subsumption architecture [38]. In this scheme, the controller is built of layers with subsumption nodes. The subsumption nodes allow higher-level control layers to suppress
the output of more primitive control layers. A block level diagram is illustrated in (Figure 3-3).

![Block level diagram](image)

*Figure 3-3. Control is layered with higher level layers subsuming the roles of lower level layers when they wish to take control. The system can be partitioned at any level, and the layers below form a complete operational control system [38].*

The robot control system is made up of a series of layers, with each layer specifying a behavior pattern, implemented as a network of message passing augmented finite state machines which are allowed to suppress the actions of the layers below them [39]. According to Brooks, the subsumption paradigm allows the designer to:

- Decompose the control problem in terms of behaviors rather than functional modes
- Provides a method to incrementally build and test a complex control system
- Achieve parallel computation performed with a low bandwidth communication network with asynchronous processors in a network with a relatively fixed topology.

- Render the need for a central control module unnecessary. The control system can be viewed as a system of agents, each focused upon their world space (all notes from [38]).

Kube, et al. extended the idea of subsumption by creating a schema-based behavior control by collecting a group of actions into a composite set which is triggered by local sensor information [21]. Within those behavior sets, the controller operates with the subsumption principle. Kube also introduces the idea of sensor preprocessing, in which the position and configuration of a sensor is explicitly considered in designing the control rules in order to reduce the computational requirements of processing the data obtained from the sensor. Yoshida applies the idea in [40], in which he designs the behavior of the agents around their communication capability. In his paper, he develops a mathematical analysis of information diffusion according to the communication parameters, and then uses the findings to establish control rules.

Johnson, et al. [3] developed the behavior path control architecture, in which the resultant action is the sum of all the action commands from various behavior paths. An illustration is shown in (Figure 3-4)
This architecture differs from subsumption control in that the control outputs are additive rather than suppressive.

Another popular architecture in the literature is the ALLICANCE architecture [7, 12, 18, 20, 24, 31, 41, 42] which uses a system of 'likes' and 'dislikes' to create a 'mood' within an agent which is called a tropism. The likes and dislikes are manifested by the weights in the neural controller. The ALLICANCE architecture defines the following:

- Each robot can detect the effect of its own action
- A robot can detect the action of other robots if and only if the robot is capable of effecting the same action itself
- The robots do not lie, and are not selfish
- The communication medium is not guaranteed
- The assumption that the sensors and actuators are not perfect
• The fact that any agent, or subsystem of an agent can fail

• That if a robot fails, it may not be able to communicate the fact that it has failed

• The lack of a centralized store of knowledge (all notes from [7])

A variant, L-ALLIANCE allows for learning to manipulate the weights. Learning can be distinguished by observing learning by a single robot (ontogenetic), or learning expressed by the group as a whole (phylogenetic) [24].

3.3.4 Analysis

Analytical techniques for simulation and performance metrics vary among researchers. Ijspeert [33] declared the main problem in MAS design is the characterization and prediction of group behavior and the effect of software and hardware changes. To develop an improved modeling process, he took advantage of the idea that agents generally are simplistic, thus predictable. He then extended the idea to create a probabilistic model for simulation, in which a collective manipulation experiment can be viewed as a stochastic process based on geometrical considerations. This allows the simulation to be greatly speeded up. It is restricted to modeling simple robots in which the probability of their actions depend solely on their position in the physical space.

3.4 Cooperation

One of the largest advantages of a multi-robot system is the ability of multiple robots to cooperate in completing a task. Often, cooperation is a necessity rather than a option because of the computational and physical limitations of the robots in a group. In sum, cooperation confers the advantages of teamwork, which extends itself to teams of
low individual intelligence, which also makes the system robust against malfunction [43]. Weiss [44] said, “Intelligence is deeply and inevitably coupled with interaction.” Cooperation is generally defined as a means by which agents interact. It is desirable that, through the interaction, the general utility and effectiveness of the system is improved. For cooperative action to be possible, though, there are several requirements:

- The system needs to be distributed, that is, have more than one agent
- The system needs to be dynamic, if the system is static, an explicit cooperation protocol is redundant
- The capability for asynchronous communication
- Scalable, support weak local actions in order to enable global effects
- Reliable, able to recover from local damage, contain fault tolerance (all notes from [10])

An addendum is that in order for cooperation to be necessary, the system needs to operate asynchronously, however, when two robots engage in an act of cooperation, their actions need to be synchronized [4]. There are three possible avenues for cooperation; through the environment when an agent is capable of detecting changes made by other agents, sensing when agents are able to sense others directly, and communication in which cooperation protocols are explicitly carried out [18].

There are different degrees of cooperation, depending on the social network of the participants and their intelligence. Non-intelligent cooperative actions arise by the nature of the stimuli-response patterns without intelligent input, observed in social insects, also referred to as eusocial behavior [18]. Intelligent or intentional cooperation is observed in
higher life forms such as humans, in which cooperation is a deliberate choice on the person’s part [7]. The social structure of the collective also determines the nature of cooperation and the upper limit of sophistication attainable by the collective [6]. Stone [20] views cooperation as a commitment on the part of the agent, in order to cooperate, the agent has to commit to acting out the cooperative action. He divides commitment into three types: internal commitment, in which the agent self-binds itself to an action, social commitment, in which an agent binds with another agent in order to carry out an action, and collective commitment, in which an agent agrees to assume a specific role.

Cooperation is not clear-cut. The performance of the system as a whole can vary. Some cooperation protocols break down when the number of agents is outside a range [19]. It is possible to enable cooperation with or without explicit communication. Several studies [2, 45] have shown that communication, even minimal, improves the performance of a group. However, if the group size is increased beyond a bound, the communication infrastructure can be swamped by the demands put upon it by the agents. The rest of this section will be divided in non-communicative cooperation and cooperation with communication.

3.4.1 Cooperation without Communication

Explicit communication brings a lot of advantages along with it, most prominently, the ability to transfer knowledge. The disadvantage, however is that communication represents a resource-hungry component. Aside from the message processing issues a receiver and/or sending components have to be designed for, the power supply must be taken in consideration, as well as the bandwidth limitation issues
Communication is a deliberate act, but this element of deliberation is often missing from the cooperative interactions of simple animals [8]. It may be more advantageous for low-intelligence, low-power, low-cost mobile agents to eschew communication entirely.

Without explicit communication, it is imperative for the system to have a well-regulated method for ensuring that all possible situations the agent may be confronted with have a control response. Social conventions are rules that place constraints on agents in order to restrict the range of possible interactions [11]. In other words, all agents have the same internal structure, knowledge, possible actions, and follow the same strategy [20].

Ijspeert [33] employed a probabilistic strategy to encourage cooperation in a task requiring two agents to cooperate in pulling a stick out of the ground. Each robot has a gripper that is capable of lifting the stick. The stick however is too long for one robot to completely clear it out of the ground. A second agent is required to complete the task. An agent that is not engaged in a task roves the field. If it sees a stick in the ground, the agent pulls it partway out of the ground and holds it. If another agent encounters the first one, it pulls the stick the rest of the way out of the ground, completing the task. As the number of agents increases, the probability of an interaction occurring also increases. If the number of agents falls below a threshold, the system may get stuck at a transitional minimum, with all the agents holding sticks, waiting for another agent to complete the task.

Implicit communication occurs when an agent is capable of recognizing and acting upon a change in the environment effected by another agent. Another term for this
is stigmergy [20]. A robot may not be able to accomplish a task by itself, but it is able to change the environment such that the task is easier for other agents.

Implicit communication is prevalent in formation-keeping activities [2, 18, 25, 45-47]. Not every formation group is communication-free, however. It is desirable to have minimal communication for formation upkeep, or else the possibility that the communication channels become saturated rises [47]. Freuslund [47] requires a leader of a formation to be selected, then the other agents can orient themselves in relation to the leader. Once this is accomplished, global motion is achieved simply by having the leader move. The other agents see their assigned reference position change, and move in order to maintain their assigned position in reference to the leader. Indirect communication is more effective, however, if the individual agents have a model of the other agents, to be better able to predict their decisions [18].

3.4.2 Cooperation with Communication

Communication increases the knowledge available to each agent in the system. Different degrees of communication is possible, to go along with differing degrees of intelligence. When an agent initiates communication, the commutative act affects the dynamic environment; in order for the communication to be meaningful, a framework has to be in place so that preconditions and effects of communication are defined [20]. This point of view looks upon communication as an action, or speech acts as opposed to the standard communication analysis that focuses on the communication channel itself as means of conveying information [8]. Using communication to enable cooperation
consists of two steps: communication of the task parameters to the agents involved in the task, then the communication of data required to complete the task itself [48].

Traditional communication protocols focus on enabling reliable and efficient transmission of information, deemphasizing the content of the message. This approach increases the overhead required for the communication act, in acknowledgement and synchronization protocols. In MAS, there usually are multiple levels of redundancy, thus point failures in the communication network are tolerable. Rather, the content of the message is the focus [9]. Also, when using communication for action planning, there arises the possibility for agents to ‘lie,’ that is, to deliberately communicate misinformation in order to satisfy a goal [20]. Smith [9] developed a cooperation protocol based on two agents creating a ‘contract’ to cooperate. The agent in need of resources sends out a bid, which consists of the task in process, and the resources needed. Agents that receive the bid have the option to respond or not. After agents respond, the contract negotiation process starts. The initiating agent processes a cost analysis to determine which agent it awards the contract to. Smith also allows for abstract representation of a message, breaking the message down in object, attribute, and value representation components. This flexibility allows the communication architecture to incorporate semantics that not all agents are able to understand. Thus, ‘private’ information can be incorporated in public messages, those agents who do not understand the private part can safely ignore it.

Once the decision is made to incorporate communication, it is not necessary to become completely dependent upon communication to convey data. Communication
systems have limitations inherit in their operation, as mentioned earlier. One method to reduce explicit communication is to implement implicit communication, when agents communicate through changing the environment other agents pass through [42]. Fukuda [4] incorporates this view in designing agents with the capability to model other agents. The agents are also aware that their model is not perfect, and constantly estimate the error of their predictive model. When this error rises above a set threshold, the agent engages in a communicative act in order to obtain information to reconstruct accurate models of other agents, improving its prediction of the actions other agents will undertake. Local communication reduces the probability of bandwidth saturation. Yoshida [48] adjusts the local communication range of individual agents dependent upon the optimal frequency of commutative acts such that the communication channel is not saturated. In his analysis, he shows that it is possible to reduce the global communication frequency by adjusting the local communication area of individual agents.

With a relatively small number of agents, it is possible, or even desirable, to have a high frequency of communication acts. Rybski, et al, [49] developed an surveillance system employing small cylinder-like robots that they call Scouts. Because of their size, however, the scouts have very limited processing power which is almost exclusively spent on self-locomotion. All the data processing and decision making processes are offloaded through a radio link to a more computationally powerful processor via a radio link. This creates a performance bottleneck for the system, more scouts allow more area to be mapped, but the communication channels become saturated much faster, increasing latency in decision processing. The scouts are essentially a single-robot teleoperation
scheme. On the other side of the spectrum, Brumitt, *et al* [50] employs highly intelligent autonomous vehicles to plan out driving routes for mapmaking or task completion. To achieve this, they employ a high-bandwidth communication channel between vehicles in order to be able to create a complete environmental map, and trade current individual and global mission goals.

Occasionally, global communication is desirable. However, this carries its own set of problems with it. With a large number of agents, it is possible for the total volume of information to exceed the agents' processing capability [40]. In metamorphic robots, if the communication network topology is acyclic, then global message propagation is guaranteed if each node transmits the message to all of its neighbors [10]. If the network is cyclic, however, measures have to be taken to ensure that messages do not enter a continuous loop. Ichikawa [43] developed a global communication protocol that concentrates solely on the transmission of the message. Without acknowledgement signals, each node transmits all messages that it receives. If the communication areas of the agents overlap, message saturation is guaranteed. This is demonstrated in (Figure 3-5).

*Figure 3-5. Connections of communication network in the case of 50 robots [43].*
This communication protocol gives the advantage of creating an *ad hoc* network. An explicit network does not have to be established every time a message is transmitted. Numerous communication channels are also rendered unnecessary. This scheme also allows for a central information store implicitly. A central information store can take note of all global messages transmitted throughout the network, and then perform any necessary operations [51].

### 3.5 Biological Agents

A lot of research in MAS has drawn ideas from biology. This section reviews the background of biological agents from the perspective of control analysis. Some applications are looked at.

It is an easy decision to look to biological systems for inspiration. Nature has had millions of years to search the parameter space for incremental optimization. Flocking, herding, schooling behavior has been observed in all levels of species complexity. Distinctions between types of social organizations has been made, schooling fish employ unilevel organizations, higher species, such as baboons participate in hierarchical systems, whereas lower social insects engage in caste division [6]. Much interest has been focused on the social insects because insects, individually do not have much intelligence, but collectively, they exhibit a complex society. Their aggregate behavior can be viewed to have greater complexity than the social interactions of other species [20].

Insects engage in distributed task allocation, colony-level behaviors emerge from simple interactions between individuals based on a set of rules based on local information
The high level of complexity observed in social insects may have been a result of a set of evolutionary cost analysis decisions; individuals in simple aggregates are more productive than sole individuals in groups with cooperation, which then are more productive than individuals in aggregations without cooperation [19]. Kube and Bonabeau [5] reported an observation of the behavior of ~100 ants belonging to *Pheidologeton diversus* which were able to carry an earthworm weighting 1.92 g and 10 cm long at a speed of .41 cm/s. Each worker ant weighted .3-.4 mg, which works out to each ant carrying approximately 50 times its body weight. If those ants engaged in solitary transport, they would be able to carry, at most, five times their body weight. Cooperative transport yielded much greater carrying capability with a small loss in velocity. In an observation of another species of ant, the total weight of an object a group of ants were capable of carrying varied in proportion to the number of ants raised to a power of approximately 2.

A large part of the problem of task assignment is in determining when to switch tasks. Insects, like robots, do not have much computational power devoted to decision making. Thus, any task assignment transition scheme must be very simplistic. One such model is the activation-threshold model [19]. A schematic is shown in (Figure 3-6)
Figure 3-6. Individual choice between two activities with a fixed activation-threshold. Neglecting activity 1 causes the stimulus for activity 1 to increase, prompting individuals to change from activity 2 to activity 1; and conversely [19].

In this model, individuals react to stimulus that is linked to the task itself. When the threshold activation of a stimulus is reached, the insect changes its action to carrying out the task linked with the stimulus until another stimulus threshold is reached, triggering a task change. This model also allows for non-specialized insects to engage in work if the specialized insects are unavailable. Non-specialized workers have a higher threshold activation level than the specialized workers, so they will not be triggered to engage in work unless the specialized insects are not capable of reducing the stimuli level by performing the task linked with the stimuli.

Information processing in insects is simplistic because insects take advantage of the constraints they live under [26]. Kube, et al [21] have suggested that insects simplify
complex decision making processes by having specialized sensors. The organism’s solution to perceptual tasks “is often restricted to a narrow range of stimuli and situations found in its environment” [21]. For instance, ants and crabs have visual streaks in their eyes, areas of concentrated density of visual receptors on a horizontal line through the center of the eye, which matches the horizontal world that they inhabit. Kube calls this evolutionary trait matched filtering, that is, sensing receptors spatially arranged to match environment-specific stimuli. Kube extends this behavior to robots by having state transitions in behavior be triggered by perceptual cues. In this mechanism, sets of environmental cues are grouped such that there is one-to-one relationship between the perceptual cues and triggered action, so that diverse and independent stimuli can lead to an additive effect on behavior. In this manner, sensors can be perceived binary triggers, without the overhead of sensor processing. The guiding principles of Kube’s model are:

1. Sensors are environment-specific, designed in such a way to reduce the need of preprocessing
2. In task decomposition, the response associated to a specific set of sensor stimuli only needs to be mutually exclusive within the tasks themselves
3. Ensure that behavioral transitions are governed by orthogonal stimuli, a set of stimuli that does not conflict with each other
4. Individual behaviors can act negatively toward the completion of the task, so the number of agents involved needs to exceed critical mass so that the vector toward task completion is greater than individual disturbances (all notes from [21])
The last point bears exploring. In another paper Kube [5] states that the randomness and fluctuations in individual behavior may not actually be detrimental but rather may greatly enhance the system's capability to explore new behaviors and solutions.
4 Hormones as a method of communication and control

4.1 Introduction

In this section, the structure of the communication and control architecture using hormones is presented. First, the rationale for the need of this architecture is discussed. Definitions of several key terms are presented. The similarity between the hormonal system as presented in this model are compared to that of the human endocrine system. Contrasts are also be made between the hormone representation of this model and that of Wei-Mei Shen [10, 17, 22, 34].

4.2 Definitions

Many different definitions have been given to various terms throughout this paper. In this section, the definitions as used by the Hormonal Communication and Control (HCC) architecture will be established.

4.2.1 Hormones

In the HCC model, a hormone is a packet of data consisting of the following information

- Base hormone
- Time-To-Live
- Modifiers

The hormones can be thought of as an encapsulation of state information. Hormones represent an intermediary form of interpretation of the divergent perceptions of the agents themselves. Hormones are only generated by the agents themselves when they detect a divergence from homeostasis. A high-level agent or a human observer can
choose to distribute a hormone without accompanying stimuli in order to evoke a desired action in the system. The hormone can be thought of as being similar to a content-based message, but differs in that it triggers different actions in different agents, but leaves the execution and coordination of those actions to the local agent which receives the hormone [22]. More specifically, the differences, as defined by Shen [10] are

- Lack of specific routing information
- Propagates throughout the network
- May have a lifetime
- Triggers different actions for different receivers

The base hormone is the minimal amount of information needed to convey the system state. Each hormone represents a type of deviation from homeostasis. It is not necessary for the hormones to be mutually exclusive. A designer can determine that two hormones for the same type of deviation are necessary, but with one being more potent than the other.

The Time-To-Live segment limits the distribution of the hormone. If the field is empty, then the hormone will be distributed globally, that is, the hormone will be repeatedly transmitted until every agent within range of the transmission has relayed the hormone itself. Otherwise, this field represents the number of node hops the hormone is allowed to take, and the number of hops a specific copy of a hormone has already taken. If the number of hops is equal to the maximum allowable, then the receiving agent does not retransmit the hormone. If each individual agent has a communication radius R and
the maximum number of hops is \( h \), then the maximum communication area in which the agents will receive the hormone is expressed in (Equation 4-1).

\[
CA = \pi hr^2
\]  

Equation 4-1

The modifiers create isotopes of the base hormone. In general, moderators carry the parameters of the hormone which will affect the excitatory level that the hormone simulates in the receiving agent. Not all of the agents which the base hormone affects will be affected by the modifiers.

4.2.2 Homeostasis

Homeostasis is a state which is defined to be the desired quiescent state of the system. The design decision of the valuations of the parameters of the system follows from the decision as to what the homeostasis state is. After the definition of homeostasis is established, then the degree of deviation from homeostasis which will induce hormone creation can be determined. The parameters which make up the definition of homeostasis need not be constant. However, if they are altered, then the hormone generator of each agent will have to be updated before the new parameters take effect. Deviations from homeostasis can be induced by high-level agents, as the central nervous system does through the hypothalamus in humans [13].

4.2.3 Computational cost

In this application, computational cost is defined as the time required for a computational operation to be accomplished. The time required for a specific operation may vary across agents, depending on the processing and memory capability of an individual agent.
4.2.4 Complexity

A catch-all indicator of complexity is that a task becomes harder as the complexity increases. This, in turn requires a definition of hardness. In this paper, hardness, and complexity by extension is defined to be the number of control choices available. If there are a number of options available at a junction, sensor and internal data needs to be processed in order for the agent to be able to make what the agent perceives to be the correct choice. The degree of information necessary to distinguish between choices increases as the number of choices available increases.

For instance, assume that an agent’s action choice at a particular junction is dependent upon its world perspective at the time. An extremely simplistic model would be the distinction between day and night. A more complex model may include the presence of sun or stars. Determining the presence of stars first requires the system to determine if it is day or night, and then determine whether the sky is cloudy or clear, and so on. The granularity of the final model is dependent upon the decisions behind the assumptions of the less granular layers.

The complexity of a procedure is dependent upon the number of decision steps required to completely formulate the solution. Increasing the complexity of a task increases the computational cost of the task for an individual agent.

4.3 Rationale

The goal of any architecture is to enable a straightforward means of structuring an approach to a problem. Once the choice of architecture for a MAS application is made, then the parameters necessary for the individual agent control system can be determined.
Throughout the literature review, the structure and analysis of the communication infrastructure is usually reviewed independently from the control system infrastructure. That is, communication is viewed as a separate module within the functional blocks of the makeup of an agent. Many authors have emphasized the importance of communication, as can be seen in the following quotes:

- "Each module has limited capabilities but the ensemble must be able to achieve tasks in a distributed fashion, hence the intelligence must lie primarily in the interactions between modules" [28]

- "Communications is essential in a coordinated team. Without explicit communications, a robot can only interact with team members using its sensors (e.g. vision-based 'follow the leader' behavior)" [36]

- "Communication will play an important role in the development of any many-robot system, if not in its deployment and operation, since effective communication between the developer and the system elements is a key prerequisite for the tuning of system performance and the achievement of functionality based on cooperative element behaviors" [8]

Numerous authors have proposed a set of required features for a successful MAS architecture. The list presented herein is from Agah, et al [24]. The proposed architecture for any MAS system must be:

- Functional
- Robust
Adaptable to environmental changes and learn accordingly

- General enough so that it can be implemented for a variety of problems
- Hardware-independent
- Lend well to simulated evolution
- Learn in a format that is meaningful to a designer
- Modular, enabling easy addition and removal of behaviors

The following sections touch upon the points required by Agah. However, not every requirement is directly addressed. The HCC model provides the flexibility for the designer to adhere as strictly to the requirements listed as he wants.

4.3.1 Communication

In the HCC model, the communication protocol is an integral part of the control framework. The information encapsulated within the hormones serves as an independent source of sensing data, providing information on the state of the system. This will enhance the impact of individual agents throughout the system. Salemi [22] addresses hormones specifically for their advantages as a means of enabling global communication. In his view, hormones differ from broadcast or content-based messages in that propagated signals, in the form of hormones can be modified, delayed, or disappear (intentionally or not). The utility of hormones allow the functionality of the communication system to extend beyond conventional message systems [22].

In any application, having more information available to individual agents is often conducive to decision making ability and the overall efficiency of the system. Global communication has its drawbacks however. The information transmission efficiency
degrades when there are multiple agents employing a single communication channel [48]. HCC provides the ability to transmit global information on a local basis by giving individual agents authority over whether to transmit a hormone or not. This will ensure that if the density of the agents in the union of the communication area covered is high, the state information inherit in the hormone will be distributed sufficiently such that the necessary agents will be recruited without impacting the communication load outside the communication union designated by the TTL of the hormone.

Communication design that is based on transmitting packetized data has advantages over systems that require variable-length data transmission. The risk of information loss is reduced by requiring all data transmission to fit within strictly specified limits for size and composition. With a fixed format, the communication act is decoupled from the communication medium and gains the ability to be implemented in a variety of mediums, e.g. infrared, camera-based, radio. Information transmission also takes place concurrently among agents, reducing excessive information processing. The system also becomes robust with respect to the number of agents present [48].

4.3.2 Task allocation

Task division and allocation is one of the more complicated problems in MAS. Task decomposition and assignment strategies that are capable of adapting to unknown environments are essential. However, a starting point is the idea that all algorithms for task allocation have a common structure; they work at the individual level, prompting individual agents to continue or change their activity [19]. Advanced labor division implies that decision making is centralized around a series of concurrent activities. For a
system to function effectively, the number of agents involved in each concurrent activity must be regulated such that the number of agents involved approaches optimality [19]. The HCC provides a method to regulate the team size by allowing hormones to be present at all times. The agent recruited by a hormone can be provided with the ability to sense the number of agents already participating in the task, and may be computationally advanced enough to determine that its help is not needed. Conversely, agents already participating in a task can be recruited away for another pressing task if the hormonal stimuli level is strong enough. In animal societies, animals can display a specific behavior that can 'cue' an action to occur in another element, regardless of whether if the effect on the receiving element is intended or not [8]. As an example, a lone bird may take off if it detects danger. However, if the bird is in a flock, taking off can cue the rest of the flock that danger may be present, prompting the rest of the flock to take off as well. In robots, however, Gage allows for explicit cueing action because the computational capability of agents may not be sufficient to accurately identify behavioral cues. This ability is provided for in HCC by enabling agents to be able to commit to a task that it can accomplish on its own, but at the same time, allowing it to generate and distribute recruiting hormones.

4.3.3 Control System

It can be argued that the decision of what control system architecture to employ is the most important part of any design process. The distinction of the HCC architecture is that it does not specify a model for the control system. Rather, it specifies the interface between the control system and the communication system. This allows the designer to
determine the complexity of the control system independently of the communication system. The designer has the option to define how the interactions of the active hormones affect the control system decisions. For an extremely simplistic agent with low computational capability, the designer may elect to have a simple majority rule for the interface in which only the most active hormone is visible to the control system. On the other end of the complexity scale, interaction rules between active hormones can be implemented. Independently, in this sense means that hormonal interactions in the hormonal action engine as described in Section 4.5.5 are decoupled from the hormonal interactions which provide meaningful information for the control engine. The difference between the interactions of the hormones in the hormone activity engine, and the meaning of the mix of the active hormones is discussed in a later section. Any control system should not be more complex than necessary; the complexity should be driven by the demands of the problem [24]. The hormones, in themselves do not make any demands toward the complexity of the control system with which they interact. This permits the degree of complexity to be heterogeneous amongst the control systems in an agent population. Hackwood, et al [27] said about the ability to comprehend the environment, “perception of the external environment is a prerequisite to understanding, and thus of intelligence. […] understanding is essentially a process of recognition, which requires matching what is being perceived and what is known.” Grabowski [36] created a team of robots with differing intelligence and capabilities, and allowed the more intelligent robots to cooperate with the less intelligent ones. In HCC, this concept is extended. A generation of a specific hormone can require a complex set of stimuli,
which is achievable only by an agent with a high degree of computational power. However, the ability to act on the hormone does not require the same level of intelligence. Thus, for instance, in an oil spill, a high-level agent can recognize perceptual stimuli as belonging to a set that suggests an imminent oil fire. The agent then transmits a hormone that reflects a firefighting state. Low-level agents then can respond by undertaking action which decreases the overall risk of a fire even though it does not have the intelligence to be able to comprehend the eventual goal of its action. A few of the large advantages of employing hormones are: It is scalable; it does not depend on the knowledge of the number of agents that are available at any time, it is also efficient; coordination only requires one hormone, and it is distributed, hormone dispersion only requires $O(n)$ message hops, rather than the $O(n^2)$ hops required of messages originating from a central controller when $n$ messages are sent to $n$ agents [10].

The scalability of a system is a big problem in multiagent systems. The intent of the experimental simulation that is exhibited in a later chapter is to demonstrate the claim that the HCC architecture is capable of real-time scalability.

4.4 Analogues between HCC Hormones and Biological Hormones

The following table outlines some of the analogues between biological hormones and the hormones as employed by the HCC model (Table 4-1)
### Table 4-1. Comparison of biological and HCC hormones

<table>
<thead>
<tr>
<th>HCC Hormones</th>
<th>Biological Hormones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identical hormones can be produced in different areas of the body</td>
<td>Identical hormones can be produced by different robots</td>
</tr>
<tr>
<td>Specific hormones do not have a fixed form; isotopes with different forms but similar effects exist</td>
<td>Modifiers can be attached to the 'base' hormone</td>
</tr>
<tr>
<td>Potent hormones have a short lifetime</td>
<td>Potent hormones have a faster delay rate and smaller radius of action</td>
</tr>
<tr>
<td>Some hormones are effectors, some are inhibitors, and others remove inhibitors</td>
<td>Hormones can effect actions, block actions, or change the activity level of other hormones</td>
</tr>
<tr>
<td>Hormones are inactivated in various ways; eliminated by the immune system, combined with acids, or filtered out by the kidney</td>
<td>An agent can decide to halt transmission of hormones, each hormone package has a fixed TTL, the activity level of an active hormone decays with time</td>
</tr>
<tr>
<td>Some hormones can simulate production of other hormones</td>
<td>Some hormones can simulate production of other hormones</td>
</tr>
<tr>
<td>The sensitivity of the body toward a certain hormone depends upon the state of the body at the time</td>
<td>The control system can be adjusted to become more sensitive toward certain hormones when the system is in a specific state</td>
</tr>
<tr>
<td>The goal of the body is to maintain homeostasis</td>
<td>The goal of the system is to maintain homeostasis</td>
</tr>
<tr>
<td>The simplest regulatory mechanism is to have the product of the action of the hormone regulate the secretory level of the hormone</td>
<td>The simplest regulatory mechanism is the task completion, which eliminates the need to produce more hormones</td>
</tr>
<tr>
<td>The body must adapt hormonal output to counter external stresses</td>
<td>Deviation from homeostasis can be induced by injecting hormones to simulate external stresses</td>
</tr>
<tr>
<td>The link between the central nervous system and the endocrine system enables the endocrine system to be functionally related to external fluxes</td>
<td>An high-level observer can inject hormones into the system, approximating the role of the central nervous system</td>
</tr>
<tr>
<td>The response of the body is controlled by the total mix of active hormones present in the body</td>
<td>The control system can be created complex enough to consider the activity of more than one hormone at a time</td>
</tr>
<tr>
<td>Most hormonal effects are directly related to the amount of the hormone present, within limits</td>
<td>The excitatory level of hormones is modulated by a limiter</td>
</tr>
<tr>
<td>Classic negative feedback</td>
<td>Action of hormone eliminates the need to generate more hormones</td>
</tr>
<tr>
<td>Indirect negative feedback</td>
<td>The action of an initial hormone creates stimuli to generate another hormone, which effects action that curtails the stimuli for the first hormone</td>
</tr>
<tr>
<td>Short-circuit feedback</td>
<td>The control system can be created such that it is sensitive to duplicate generation of a hormone that is generated by other agents, which cuts off the stimuli to generate the hormone</td>
</tr>
<tr>
<td>Hormones are transported by the circulatory system with no specific routing information</td>
<td>Hormones are transmitted omnidirectionally with no specific routing information</td>
</tr>
<tr>
<td>Identical hormones can give rise to different effects depending upon the receptor</td>
<td>Agents can be created to be heterogeneous, which enables diverse agents to respond differently to the same hormone</td>
</tr>
</tbody>
</table>
4.5 Hormonal Communication and Control Architecture

The HCC model is applied to a group of agents in a dynamic environment. A definition of homeostasis is established by determining a set of desired parameters within the environment. The agents are able to identify when some aspect of the environment has deviated from homeostasis. When a deviation is detected, the agent either adjusts the environment such that the deviation disappears and/or generates a hormone which will recruit other agents who are able to correct the deviation. Not all of the agents need to be able to identify deviations. Agents can be created to be only capable of responding to hormones.

There are no system wide parameters. Global behavior emerges from local interactions. The response to each hormone is fixed within each agent. In order to effect system wide changes, the response patterns of each agent are adjusted.

4.5.1 Hormone Creation

The flowchart showing the steps involved in creation of a hormone is illustrated in (Figure 4-1). The sensors of the agent collect environmental data. The priority determination is employed for agents with low computational capability, to prevent the homeostasis test from being overloaded. For the creation of more complicated hormones, input from several sensors will have to be integrated while testing for homeostasis. More computationally advanced agents will not need the priority determination step. The homeostasis step determines if any deviation exist between the environment and the internal model of homeostasis. If no deviation exists, then there is no need to create a
hormone. However, if a deviation exists, then the system starts the steps toward creating a hormone. Each agent has an array of hormones from which it can select from. Not all of the hormones available in the system will be included in the list within an individual agent. The base hormone list of each agent only contains hormones which enumerates the deviation which it is capable of detecting. It is possible for a specific deviation to be associated with several different base hormones, each with slightly different degree of action. If the distinctions between the base hormones within a deviation group are subtle, then it will require an agent with sufficient computational power to correctly determine the appropriate hormone.
Once the base hormone is selected, the agent also determines the TTL, or the range of distribution the hormone should have. An empty field for the TTL indicates that the hormone should be globally distributed. Otherwise, the number of agent-to-agent hops the hormone can make is limited to the TTL value established. It is possible for a specific hormone to have a variable or fixed TTL values.

Modifications are any extraneous factors which will affect the stimulatory strength of the hormone at the recipient or to inform intelligent agents of finer
distinctions. This can include the number of agents already participating in the task, whether if the deviation requires immediate attention and so on. It also can contain data which is comprehensible to agents with the computational ability, which will be ignored by agents who do not have the necessary infrastructure to interpret the modifications.

4.5.2 Hormone Decomposition

Once an agent receives a hormone, it has to decompose it in order to be able to determine the stimulatory level of the hormone. The following illustration shows the steps involved (Figure 4-2).

![Diagram](https://via.placeholder.com/150)

*Figure 4-2. Decomposition of a hormone*
When the hormone is received, it is split into three parts, the base hormone, the TTL, and modifications. The base hormone is compared to the list of the hormones the agent is able to respond to. If the agent is able to respond to the hormone, then the base hormone and the modifiers are bundled and sent to the state determination engine.

If the hormone does not exist in the agent list, the agent is not able to take action on the hormone. In this case, the process turns to determining whether if the agent should act as a new node of transmission. The agent checks the TTL data to find how many hops the hormone has made. If the value is less than the maximum set, then the agent will increment the number of hops made value and then bundle everything together and send it back out. If the number of hops already made matches that of the maximum TTL value then the agent stops processing, effectively killing the hormone.

4.5.3 State determination

State determination is the process in which the agent gathers data from its sensors and the state data encapsulated in any currently active hormone and builds its internal representation of the world state. The flowchart of this process is shown in (Figure 4-3)
The hormone/controller interface determines the amount and nature of the information provided to the control system. The operation of the hormone/controller interface block is explained in a later section.

The representation given here is simplistic. The function of the State of System, State of Immediate Environment, and Action Engine is specific to the agent, system, and the problem application. However, the State of System and the State of Immediate Environment create outputs that can be compared with the internal homeostasis model of the agent.
4.5.4 Hormone Activity

The hormonal activity engine regulates the initial activation signal. It also controls how the hormonal stimuli apparent to the decision engine decays over time. The control schematic is shown in (Figure 4-4)

In biological organisms, hormones are physically manifested by organic molecules. Thus, by dealing with the molecule itself, the concentration of the hormone in the circulatory system is adjusted. To destroy the hormone, the organism just needs to alter the hormone such that it is not biologically active anymore. In this application, however, hormones are envisioned to be distributed via a communication structure.
Thus, it is possible for more than one agent to receive a hormone that is transmitted by one agent. So, a mechanism to control the activity of the hormone is necessary.

Within the agent exists a hormone storage module which updates the activity of the active hormones in the agent. This storage method is demonstrated in (Figure 4-4). The basic model of hormonal activity is a negative feedback loop which exponentially decays the activity of the hormone with time. The decay scheme can be linear, exponential, or any relation. Depending on the desired application, the decay constant can be adjusted.

Interactions which inhibit or enhance the activity of the hormone are possible. This is reflected by adjusting the activity level of the stimuli within the feedback loop. It is possible to imagine of a situation in which multiple agents detect a single source of deviance which prompts a hormone generation. In this case, an agent possibly will be flooded with a great number of distinct identical hormones. To prevent the activity level from overwhelming the activity of other hormones present in the agent, there will be a limit to the maximum activity of any single hormone.

Two or more hormones can have a relationship with each other. In this situation, the activity of a ‘parent’ hormone selectively excites or inhibits the activity of a ‘child’ hormone. For instance, the capability of an emergency attention system may be desired. In that case, a hormone can be designed such that once active, it actively inhibits the activity of every other hormone in the system. In another case, suppose one of the goals of the system is to search for energy sources, if a Nest Energy Low hormone is active; its activity may increase the sensitivity of the agent to an Energy Location Found hormone.
4.5.5 **Hormone/Controller Interface**

A detailed description of the control system design is beyond the scope of this paper. However, the nature of information processing done in the interface will be discussed.

The goal of the HCC is to enable agents with specific abilities to be recruited from reasonable distances within the system to cooperate in maintaining homeostasis. In order for this to occur, the control system must be receptive to input of the hormones. The complexity of the control system is dependent upon the function of the agent and its computational capability.

It may be desirable to have the whole active hormone mix to take part in the decision of what action to take at the moment. In this application, it may be a prudent choice to employ a fuzzy controller. Interactions amongst several different hormones may or may not be governed by simple rules.

With agents with very low computational ability, it may be sufficient to employ a simple activation threshold model, such as the one shown in Figure 3-6. In this model, only one hormone is active at any time. When the stimuli from incoming hormones elevate the activity over a specific threshold, the agent will switch tasks.

The mechanism of task switching or allocation is a central part of the success of any distributed system. Careful thought will have to be put in the proper choice of the mechanism.
4.5.6 Node

The subsystems discussed above are put together in one flowchart, which is illustrated in (Figure 4-5)

![Flowchart Diagram]

Figure 4-5. Agent Node

4.5.7 Designer Determined Parameters

One of the intentions of the HCC architecture is to give the system designer the widest latitude possible in combining agents and tasks. The manner in which hormones manifest themselves has been discussed in great detail. The physical implementation is not specified. In this paper, the implementation method is discussed as a model of radio-based communication. However, hormones are not constrained to one communication
medium. Any kind of stimuli can act as triggers for hormonal activation, be it radio, visual, tactile, smell, or TCP/IP packages over the Internet.

The most important decision the designer has to make is the interface between the HCC architecture and the control system that the designer has chosen to utilize. The conceptualized output of the HCC architecture is a partially observed global system state as it pertains to each individual agent. This output will need to be transformed to a form that makes sense to the control system be it a fuzzy logic, neural network, PID, or an activation threshold controller. That is the responsibility of the hormone/controller interface.

The differences between individual agents are seen in the preprocessing of the hormones. The prevalent role of an agent is determined by the degrees to which hormones are active in its internal representation. In a hunter-gather society, it would take longer for the emptying larder to prompt the hunters to join the gatherers in the field. In contrast, it would take a large amount of fierce animals encircling the camp to prompt the gatherers to join in fighting them off. A hormone self-loop feedback system can replicate those conditions. For a gatherer, the sight of an emptying larder creates a large excitatory signal for the hormone, which dissipates relatively quickly to allow the agents to return to the home base to do non-gathering tasks. In a hunter, the loop has a low excitatory signal, but a slower delay constant to allow the signals to accumulate if they come within a short span of time.
5 Mine Detection

5.1 Introduction

This chapter applies the HCC model to the mine detection problem. The mine detection problem was chosen to provide comparisons with other models. The rationale for the problem is provided. Two other models applied to the mine detection problem are discussed, and comparisons between the HCC model and the other models are detailed. The implementation of the model is then discussed, and results presented.

5.2 Rationale

In order to gauge the effect a new model will provide to problems that are original, it is imperative to apply the model to a baseline problem. In this manner, a performance relation between the baseline problem and the new problem is developed. Also, insight toward how the model approaches the problem can be gleaned by comparing approaches.

5.3 Mine Sweeping Problem

The mine detection problem as presented in [52-57] consists of a constrained space. The space is initialized with a set number of mines distributed randomly across the space. The agents start at the edges of the space. The goal is to detect and defuse all of the mines. The defusing of the mines is accomplished by gathering four agents around the mine in the cardinal directions. This problem is of interest because it requires agents to cooperate in order to complete the goal. However, the degree of cooperation varies from model to model. Mapping information can be shared between agents during foraging or not. A variety of recruitment methods can be employed as well. The
problem also gives opportunity to explore strategies to avoid freezing [56], a situation in which agents attach themselves to mines in the space in such a manner than no mine has the full compliment of four agents necessary to defuse it. If measures are not taken to break out of the frozen state, the agents can remain in that way indefinitely.

5.4 Comparisons between models

Two models have previously been applied to the mine detection problem: the ant colony model and the artificial immune system model. The ant colony model [55, 57] consists of agents capable of laying a scent. The scent varies in strength, and the goal of the model is to have a scent gradient around mines such that the agents will naturally traverse along the gradient and arrive at the mine itself. Communication in this case is stigmetric, in that the agents change the environment in such a manner that attracts the response of other agents.

The artificial immune system (AIS) model [52-54] incorporates the concept of the artificial immune system in organisms. In broad terms, systems are distinguished into two partitions, the self, which refers to the intelligent system which coordinates the action. The self agents are contrasted by non-self agents, or foreigners in the scenario. The self agents react to the foreign non-self entities as the immune system does, generating antigenic epitopes, which can be interpreted as actions. The immune network is analogous to the communication network [54]. In the mine detection problem, the agents are the self agents, the mines are the antigens. When an agent detects a mine, it generates and transmits antigenic epitopes, attracting other agents to the mine.
In implementation, the HCC model appears very similar to the AIS model. This is a result of the restricted set of actions the agents can take. Both the HCC and AIS models make use of explicit communication for recruitment purposes. The difference lies in how the data communicated by explicit communication is viewed. In the AIS model, the intention of communication is to provide the mine location. The communication is interpreted as a piece of data to be acted upon. In the HCC model, the communication network carries hormones. Those hormones do not exist indefinitely. The hormones decay with time, and eventually disappear if they are not reinforced. One way to view it is to consider the hormones as temporary memory elements storing information on systems state. The HCC model also provides an avenue for hormones to be destroyed. The agent’s perception of the system state is dependent upon the hormones which exist within the agent. The hormones used in the model and the interactions with other hormones will be detailed in more depth as the simulation implementation is discussed.

5.5 HCC implementation of the mine detection problem

The solution design begins with the assumptions made about the problem itself. For the mine detection problem, the assumptions are as follows:

- The radius of the sensory circle and the communication circle are parameters that can be varied
  - The sensory circle parameter is within reason
The communication circle parameter can span the whole space although spanning the whole space is not the optimal value for the communication radius parameter.

- Agents are able to distinguish between a mine and other agents.
- There is no global coordinate system shared amongst agents.
- Agents are able to estimate which direction a transmission originates, as well as the distance to the transmitter.
- Hormones transmitted for more than one hop include the estimated heading and distance of the original transmitter as calculated by the agent retransmitting the hormone.
- The four-agent configuration pattern to deactivate a mine is in the form of a vertical-horizontal cross rather than a diagonal one.

5.5.1 Homeostasis

For the hormones to have any import, the desired steady state of the system needs to be defined. In the mine detection problem, the only distinguishing character of the environment an agent is able to perceive is the presence of a mine. Thus, homeostasis is defined to be the lack of mines. In other words, the desired global homeostatic balance is the solution of the problem.

5.5.2 Hormones

Two hormones are defined for this problem: the Mine Found hormone and the Mine Defused hormone. The Mine Found hormone is transmitted when an agent is next to a mine and its internal conditions allow for a hormone to be transmitted. The internal
conditions required for transmission will be discussed when the flowchart of the agent is detailed.

The Mine Defused hormone is transmitted upon successful defusion of a mine. The purpose of the Mine Defused hormone is to act as a feedback agent, destroying Mine Found hormones. The agents have their internal representation of the origin of the Mine Found hormones. If the estimated location of a Mine Found hormone corresponds nearly with that of the origin of a Mine Defused hormone, it is destroyed.

5.6 Agents

The agent behavior is compromised of three separate action sequences: searching, going to a mine, and locked on. The flowchart of the minesweeping agent is shown in (Figure 5-1). The flowchart shows the behavior that is undertaken before the agent makes mode-specific decision of action to take. External communication reception is taken care of independently of the mode of the agent.

The agent internal hormone representation consists of two lists. The go-to list contains hormones that correspond to existing mines, as far as the agent knows. The ignore list contains hormones that the agent does not pay attention to. The ignore list is used to prevent freezing situations.

To encourage cooperation, external hormones are assigned greater strength than internally created hormones. Thus, it is possible for an agent to locate a mine within its sensory range, but still prefer to navigate to the location of an externally created Mine Found hormone.
Figure 5-1. Flowchart of the minesweeper agent
5.6.1 Searching

The searching behavior corresponds to the neutral system state. Homeostasis was previously defined as the lack of mines. Thus, the searching behavior is engaged when hormones are not present in the agent. The flowchart of the searching behavior is shown in (Figure 5-2).

The agent randomly moves till either an external Mine Found hormone is received or a mine lies within the sensory range of the agent. If the agent detects a mine, it first checks if the mine is on the ignore list. If it is, the mine is ignored, and a Mine Found hormone is not generated. Otherwise, the agent now has a target to move forward to, so it switches to the go-to mode.
Figure 5-2. Flowchart of the search mode
5.6.2 Go To

In the go-to mode, the agent has a location that it is trying to get to. The flowchart is shown in (Figure 5-3). As long as the hormone exists, the agent assumes that the actual mine is still present. The hormones in the agent’s system are prioritized according to the equation

\[ p = \frac{(hormoneStrength)^2}{distance} \]  

Equation 5-1

Thus, it is possible for a selected mine to not be the closest mine. Also, more current hormones are biased because their strength is greater than older hormones which have decayed.

If the agent detects a mine within its sensory range which corresponds to the mine with the highest priority, it switches to the locked-on mode, which guides the agent through the final defusion sequence.
Figure 5-3. Flowchart of the go to mode
5.6.3 Locked on

The locked on behavior mode handles the decision of whether to transmit a Mine Found hormone, tests for the freezing condition, and finally defuses the mine if the defusing condition is met. Another important consideration is the recruitment of other agents. The flowchart is shown in (Figure 5-4).

Once the agent settles in a slot next to mine, it counts the number of agents around the mine. The decay rate of the Mine Found hormone is proportional to the number of agents around the mine. The reasoning is that it is more desirable to recruit more agents to a mine that already has agents waiting. Increasing the decay rate forces the agent to issue a Mine Found hormone more frequently. Also, the more agents there are around a mine, the longer they are willing to wait for another agents. If the wait period expires, the agent places the current mine on the ignore list, so that it will not be attracted to the current mine in the next few time steps.
Figure 5-4. Flowchart of the locked on mode
5.7 Simulation

The simulation is written in Objective C using the Swarm agent programming library [58]. Computer simulations are discrete by nature. This gives rise to several concerns that must be addressed. The way the simulation is constructed, the agents reside in a list. The simulation runs through the list, commanding each agent to perform its step. Thus, cases arise that agents on the top of the list may change the environment in such a way the behavior of the agents on the bottom of list is altered. If the list order is fixed, then the bias lies with agents who are able to perform their step first. To even out the bias, the list of agents is shuffled randomly after every time step of the simulation.

In the original design, the locked-on agent transmits a Mine Found hormone only if it is the first agent to arrive at a mine. However, in the flowchart, the final step of the agent is the motion sequence. In the next time step, the agent tries to determine whether if it is first at the mine. Thus, it may happen that two or more agents arrive at a mine in one time step. In the next time step, both agents determine that there is more than one agent present, so they assume that the Mine Found hormone has already been transmitted. To address this, agents transmit the Mine Found hormone when they first reach a mine regardless of the number of other agents present.

Another issue is the hormone transmissions. In a continuous time scenario, it is extremely unlikely that two agents would transmit a hormone at exactly the same time. In retransmitting a hormone, an agent could detect if another agent has already transmitted the hormone and refrain from repeating. In the simulation, the agents are allowed to transmit hormones without regard to other agents. The communication space
object only allows the first hormone in a certain area to be viable. If the communication space object receives additional requests covering the same area in the same time step, they are ignored.

5.7.1 Parameters

There are a few designer-adjustable parameters for the simulation. The initial input strength and the decay rate of the hormones can be set. Also, the communication radius and the sensory radius of the agents can be adjusted. In any one simulation run, the search space size, number of agents, and number of mines is set.

5.7.2 Scenarios

In this section, an overview of three scenarios is presented. The first is a normal course of minesweeping with 200 agents and 200 mines on a 100x100 field. Two cases of intentionally frozen agents, where there are five agents and two mines. In the first of two cases, the agents are within communication range of each other. In the second case, the agents are not within communication range.

5.7.2.1 200 agents, 200 mines on a 100x100 field

Snapshots of the field in time are shown in (Figure 5-5). In the first frame, when t=0, the starting position of the agents can be seen to be on the sides of the field. At t=4, agents start adhering to mines. The circles represent transmitted Mine Found hormones, shades represent the nth hop of the hormone. At t=17, Mine Defused hormones can also be seen. At t=42, interesting things start to become apparent. Initially, the agents are traveling toward a Mine Found hormone. If they fail to reach the mine in time,
agents will have defused the mine and transmitted the Mine Defused hormone. Upon reception of the Mine Defused hormone, the agent erases all hormones falling within a circle of sensory radius/2 of the estimated location where the original Mine Defused hormone was transmitted. That frees up the agent to move on to the next hormone in its priority list. The agent closest to any individual mine will reach the mine first and transmit a Mine Found hormone, inducing nearby agents to go toward the mine. In that manner, the agents start to group in small clumps. This is even more apparent at $t=183$
where there are three major groups. At $t=243$, an disadvantage is apparent, however. The main groups have headed away from the small group of remaining mines, leaving very few agents in the area. However, once a transmission chain is formed by allowing hormones to hop across a few links, the other agents eventually migrate toward the remaining mines. In this scenario, the minesweeping run was finished at $t=283$.

5.7.2.2 Frozen state within communication range

For cooperation to be beneficial, it is necessary to be able to recruit agents away from a current task in which it may be frozen. This scenario in (Figure 5-6) shows two mines located within communication range.

![Snapshots of frozen state where mines are within communication range](image)

*Figure 5-6. Snapshots of frozen state where mines are within communication range*
At \( t=2 \), it can be seen that the agents at the mine on the left is transmitting a Mine Found hormone, which reaches the agents at the mine on the right. At \( t=40 \), the agents on the left already are retransmitting again, whereas the agents on the right have a smaller decay rate, thus haven’t transmitted a Mine Found hormone. At \( t=51 \), the repeated transmission of the Mine Found hormone from the agents on the left have impelled the agents on the right to leave the mine and go to the mine on the left. At \( t=60 \), the mine has been defused, and by randomly wandering, the agents quickly latch on the mine on the right and return to defuse it. Both mines were defused at \( t=71 \).

5.7.2.3 Frozen state not within communication range

In (Figure 5-7), the two mines are located outside the communication range of the agents. This can be seen at \( t=3 \), where there is two transmissions of the Mine Found hormone. At \( t=40 \), the agents on the left transmit first because their decay rate is larger. At \( t=325 \), the agents at the mine on the right have given up on the mine and reverted to the searching mode. However, they do not wander within the communication range of the agents on the left, so the mine is not defused. Eventually, the agents at the mine on the left give up as well and wander about. It is not until \( t=811 \) when the agents finally get together to defuse the mine.
5.8 Results

In this section, the results of the experiments done with the simulation are presented. All of the experiments were run 10 times for each point of interest.

The minefield size was set at 50, 100, and 150 pixels square. In the 50x50 field, the maximum number of agents and mines were 100 (Figure 5-8). In the 100x100 field, the maximum number of agents and mines were 200 (Figure 5-9). In the 150x150 field, the maximum number of agents and mines were 400 (Figure 5-10).
Figure 5-8. Average of 10 minesweeping runs on a 50x50 field
Figure 5-9. Average of 10 minesweeping runs on a 100x100 field
Figure 5-10. Average of 10 minesweeping runs on a 150x150 field

It is clear from Figs 5.8-10 that the number of agents has a dramatic effect on the simulation time required to clear the mines. That can be attributable to the density of the agents on the field. The denser the agents are, the higher the probability that they are within communication range of one another, allowing the agents to recruit effectively.

The effect of the input gain and decay constant parameters on the performance of the agents was also tested. The result is shown in (Figure 5-11). The effect of variations in the input gain is not as discernable as the effect of variations in the decay constant. This may be attributable to the interaction of the two hormone types, Mine Found and Mine Defused. If the Mine Defused hormone did not exist, setting the input gain to a large number would force the Mine Found hormone to persist.
The agents would all have to travel to the estimated location of the Mine Found hormone in order to verify whether if the mine still exists. However, with the Mine Defused hormone present, how long the Mine Found hormone naturally decays is not as big a factor. The decay constant, however allows the hormone to persist long enough for the agent to make the trip to the mine. When the decay constant is large, the agent continually ‘forgets’ about an existing mine, leading to vast inefficiency. The effect on hormone production can be seen in (Figure 5-12).
Figure 5-12. Hormone transmits over parameter sweep on a 50x50 field

Hormone transmission is more dependent upon the decay constant rather than the input gain. When hormone turnover is high, the number of hormone transmissions dramatically increases. To gauge the effect this has on simulation time, (Figure 5-13) shows the ratio of hormone transmissions to simulation time required to complete sweeping.
Figure 5-13. Ratio of hormone transmissions per time over the parameter sweep on a 50x50 field

If the idea is that it is desirable to extract the maximum utility from each transmission, the ratio of transmissions per time should be low, and that is what is apparent when the decay constant is low. The increase in the ratio is not quite so dramatic because the time required for the simulation run to complete is increased too. However, more total hormones are required for the simulation to complete.

Another parameter of interest is the communication and sensory radius. A sweep of the communication and sensory radius is shown in (Figure 5-14).
The large number of hormones transmissions required when the communication radius is small is understandable. When the communication radius is small, the effective area of a hormone transmission is smaller, thus more repeated transmissions is required to reach the same number of ants. When the sensory radius is small, the communicated hormones have a larger role in guiding the agents to the mines. However, when the communication radius is above about 5, the performance remains the same. This is attributable to the strategy of priority selection. Even if the hormone transmission covers a large area, the agents are not induced to travel toward mines that are far away. The number of hormone transmissions over the radius sweep is shown in (Figure 5-15).
The number of transmissions is not dependent upon the communication radius. This makes sense because spontaneous transmission of the Mine Found hormone only occurs when the agent is at a mine, and in every run, the number of mines is constant. The number of hops a hormone is allowed to take remains constant. However, if the communication radius is large, the number of hops allowed can be decreased. That may have an effect on the number of transmissions necessary.

5.9 Conclusions

The minesweeping problem was chosen to provide a baseline comparison of performance relative with other models. The difference between the HCC model and the ant colony model was discussed and determined to be the method of communication.
The HCC model is dependent upon explicit communication for a framework by which hormones can be transmitted. The HCC model is similar to the artificial immune system model in that it employs communication. However the HCC model treats the information recovered from explicit communication than the AIS model does. In the HCC model, the communication data performs the role of temporary memory storage, roughly paralleling the actual system state of the minefield. The makeup of the agents were detailed and discussed. The freezing scenario shows that communication is a vital part of the HCC model, allowing recruitment. The HCC application to the mine detection problem was examined by changing the available parameters. Within small variations in the decay constant, the relationship between the Mine Found and the Mine Defused hormones reduced the influence of the variations in the internal strength of the hormone. However, as stated, the difference may lie in the use of the Mine Defused hormone as an inhibitory hormone.
6 Ants

6.1 Introduction

This chapter is a prelude to the simulation that is described in the chapter following this one. The simulation will roughly model the behavior of an ant colony. This chapter offers background material on the behavior of ant colonies.

6.2 Properties of Ants

Insect societies have been alluded to being factories within fortresses in that they gather food and raw materials from the outside world, which they employ to maintain their nest, or infrastructure, and their workers [59].

6.3 Behavior of ants

The majority of the traits shown in the colony has been drawn from wood ants because they show a pattern of forming and abandoning branch nests according to the environmental and colony needs [60]. Also, wood ants have been heavily studied in the literature.

For our purposes, the examination is divided into four categories

- Individual characteristics
- Nesting/brood care
- Food foraging
- Colony life cycle

6.3.1 Individual Characteristics

This section looks at behavior on the individual level of the ant. Ants excel supremely in the problem of task division. Ant societies are generally divided in physical
castes: queens, drones, and workers. However, in some species, the workers are divided even further. In the *Eciton burchelli*, there are four distinct physical castes for adult workers, more than any known species [61]. In other species, there is partitioning within the task itself. In *Ectatomma ruidum*, hunting behavior can be divided into stinging (killing the prey) and transport (carrying the corpse back to the nest) [62]. An individual ant is able to transition between the two partitions as the situation demands. Theraulaz, *et al* [62] hypothesizes that this behavior is the result of a stimuli-response threshold activation discussed earlier in the paper. That is, stimuli emanate from the relative number of live prey and corpses, and the degree of those stimuli trigger the stinging or transport behaviors, respectively.

Differences in individual behavior are mainly determined by the caste to which the ant belongs. Ants also change their behavior over time. The combination of the caste and temporal polytheism determine the resultant behavior of the ant. Each combination of caste and temporal polyethism has its own thresholds to environment stimuli that trigger behavioral acts. Each ant is capable of 20-45 behavioral acts [63]. However, a single task may consist of several behavioral acts. Brood care, for instance, is divided into nine distinct acts [63]. There appear to be certain individual ants who are always the first to begin a task [64]. These ants can prompt other ants to perform the same activity [60]. Individual ants can specialize in particular steps of a task. An individual ant does not need to complete the entire sequence of the task [63]. A table of the frequency of behavioral acts performed by *Pheidole dentata* is shown in (Figure 6-1)
Table 6-1. Frequency of behavioral acts

<table>
<thead>
<tr>
<th>Behavioral act</th>
<th>Minor workers (N = 1,222)</th>
<th>Major workers (N = 208)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-grooming</td>
<td>0.18003</td>
<td>0.56373</td>
</tr>
<tr>
<td>Allogroom adult</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor worker</td>
<td>0.04992</td>
<td>0</td>
</tr>
<tr>
<td>Major worker</td>
<td>0.00573</td>
<td>0</td>
</tr>
<tr>
<td>Alate or mother queen</td>
<td>0.01146</td>
<td>0</td>
</tr>
<tr>
<td>Brood care</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carry or roll egg</td>
<td>0.01391</td>
<td>0</td>
</tr>
<tr>
<td>Lick egg</td>
<td>0.00245</td>
<td>0</td>
</tr>
<tr>
<td>Carry or roll larva</td>
<td>0.12357</td>
<td>0</td>
</tr>
<tr>
<td>Lick larva</td>
<td>0.09984</td>
<td>0.02941</td>
</tr>
<tr>
<td>Assist larval ec dysis</td>
<td>0.00409</td>
<td>0</td>
</tr>
<tr>
<td>Feed larva solid food</td>
<td>0.00573</td>
<td>0</td>
</tr>
<tr>
<td>Carry or roll pupa</td>
<td>0.03601</td>
<td>0</td>
</tr>
<tr>
<td>Lick pupa</td>
<td>0.01882</td>
<td>0</td>
</tr>
<tr>
<td>Assist eclosion of adult</td>
<td>0.00818</td>
<td>0</td>
</tr>
<tr>
<td>Regurgitate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With larva</td>
<td>0.02128</td>
<td>0</td>
</tr>
<tr>
<td>With minor worker</td>
<td>0.03764</td>
<td>0.22059</td>
</tr>
<tr>
<td>With major worker</td>
<td>0.00573</td>
<td>0</td>
</tr>
<tr>
<td>With alate or mother queen</td>
<td>0.00327</td>
<td>0</td>
</tr>
<tr>
<td>Forage</td>
<td>0.12111</td>
<td>0.02941</td>
</tr>
<tr>
<td>Feed outside nest</td>
<td>0.04337</td>
<td>0.01471</td>
</tr>
<tr>
<td>Carry food particles inside nest</td>
<td>0.05237</td>
<td>0</td>
</tr>
<tr>
<td>Feed inside nest</td>
<td>0.05810</td>
<td>0.01471</td>
</tr>
<tr>
<td>Lick meconium</td>
<td>0.00573</td>
<td>0</td>
</tr>
<tr>
<td>Carry dead nestmate</td>
<td>0.01882</td>
<td>0.04902</td>
</tr>
<tr>
<td>Carry or drag live nestmate</td>
<td>0.00246</td>
<td>0</td>
</tr>
<tr>
<td>Eat dead nestmate</td>
<td>0.06383</td>
<td>0.07843</td>
</tr>
<tr>
<td>Handle nest material</td>
<td>0.00655</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 6-1. A behavioral repertory: behavioral acts by the two physical castes of the ant Pheidole dentata in an undistributed colony, with their relative frequencies. N, total number of behavioral acts recorded in each column [56].

The physical characters of ants are highly evolved. Each sense organ is specialized to respond to one type of input. Eyes respond when light falls on them. Chemical sensors are affected by a particular substance. Mechanical sensors respond
when they are deformed [60]. The inputs from the sensory organ ensure that the behavioral response is relevant to the situation, i.e. prey capture behavior only occurs if the information from the sensors indicate that a prey is present [60]. Ants can also use their sense organs to locate themselves in space. Ants are also capable of searching for an environment with a particular microclimate [63].

The lifespan of an ant is a function of the degree of the risk it experiences. Foragers are the most likely to die young, averaging 14 days from emerging from the nest [63]. Queens typically live much longer. In an extraordinary case, a queen held in a laboratory environment was observed to live for 15 years [63].

6.3.2 Nest/Brood care

A typical nest consists of a queen and her progeny, most of which are daughter workers, either infertile or less fertile than the queen. The brood consists of eggs, larvae, pupae. During certain times of the year, the queen produces fertile young male and females. As opposed to bees, which only tolerate one queen in a hive, many ant species have more than one queen in a nest [64]. Typically, however, one queen is the dominant queen [63].

The colony size varies in size from species to species. Many consist of dozen ants, however a colony of the red ant Formica was found to have 238,000 individuals. Migratory army ants of the Ection group can have up to one million members [64].

In many species of ants, colonies are not just a single structure, but rather decentralized nests networked by trails [59]. The Formica rufa, or wood ants group, create satellite nests which are used seasonally. In the winter, they withdraw to a very
large central nest. At other times, they explore their environment. If they come upon a consistent and rich food source, they may establish a new colony nearby [59].

Polydomous ant species disperse to multiple nesting sites, in the spring and summer, retreating to the core nest in the winter [63]. An instance of a species’ nesting strategy is shown in (Figure 6-2)
Polydomous ant species often exchange colony members by utilizing specialists carrying workers and immature forms, which is an important means of colony integration [63]. Hölldobler [63] states about these specialists, “It is convincible that the transporters
are engaged in allocating labor resources according to overall colony needs which, by virtue of these insects’ more extensive wanderings, they are most qualified to sense.”

Species vary in how branch or new nests are established. In some species the queen establishes a nest entirely by herself, drawing the food necessary to feed the first few workers from her body reserves [63]. Those first few workers typically are miniature forms of the workers that the queen will eventually breed [60]. This is the most common manner in which a new colony is established [63]. Other species form branch nests or new colonies by budding, in which the emigrating queen takes up to 50 percent of the older workers [64].

The colony concentrates on exponential growth for the first few generations. By adjusting the food and the care that the eggs and larva receive, the queen and the nurses determine what caste the pupae will become. The needs of the colony determine the right number of foragers, nurses, and soldiers [63].

Inside the nest, the ants engage in queen and brood care, nest maintenance, and corpse removal. The internal structure of the nest will be modeled very simplistically. Because of this, the behavior of ants in nest building and nest care will not be discussed in detail. Nor will be the procedures in caring of the brood. The majority of the ants are inactive inside the nest until they are roused for a task.

6.3.3 Food foraging/feeding

The feeding habit of ants varies. There are species on the extreme carnivore or herbivore ends of the scale, although most species are able to eat almost anything in times of necessity. Some species have a symbiotic relationship with insects, aphids in
particular. Aphids benefit from the attention of ants, becoming less vulnerable to predators, thus expanding their population [60]. In return, ants draw the honeydew that the aphids excrete.

The dietary requirements of ants differ among castes. The workers eat mainly sugary food. Lipids are imbibed by workers and some larvae. Proteins are given to the queen and larvae [63]. The replete caste is populated by ants that serve as living food storage containers. In some species, this is a permanent state, in others, it is temporary [64]. The status of the repletes reflects the food needs of the colony, which control the activities of the foragers. If the reserves of a certain type of food are full, the repletes are less likely to accept more food. The foragers are prevented from giving the food to the repletes, which in turn prevents them from going out to forage for more food. If the repletes are empty, they are more inclined to accept food of a particular type, increasing the turnover rate of the foragers which in turn increases the amount of food harvested [63].

The food reserves of the colony also control the rate and intensity of food foraging. The likelihood of foragers laying pheromone trails leading from the food source to the nest is a function of the colony food needs [63]. In lean times, however, the nurses of the brood may eat the eggs that the queen lays [60]. This behavior also regulates the size of the colony. The unfertilized eggs that are laid by some workers provide a refined food source to the queen and larvae [60].

Ants have a section in their body called the crop, used for food storage. Ants usually have food in their crop and refill frequently. When ants encounter each other, the
hungry ants may ‘beg’ for food, and better fed workers will feed them [60]. Thus, hunger becomes more of a property of the colony rather than of individual ants.

During foraging, certain ants, called scouts, are more likely to wander off the scent trail or blaze new scent trails in search of food [60]. When they find food, they will lay a scent trail back to an established path. The scout may also return to the nest to recruit nestmates to mount a raiding party, as well as guide the group back to the food source [64]. The scent trail creates a tunnel on the trail, within which the pheromone level is high enough to trigger threshold behavior in ants. Individual ants tend to return to the same location where they previously found food, and will continue to do so till the supply is exhausted [60]. Different colonies of the same species occupying an area will have 100% coverage of the foraging area without overlapping [60].

6.3.4 Life Cycle

Organisms measure successes in their ability to continue to propagate. Ants are no different. In the words of Hölldobler, the colony life cycle is an “orchestration of energy investments, in which workers are multiplied until such time as it is profitable to convert part of the net yield into new queens and males” [63]. The probability of the queen producing fertile male and female offspring increases with the colony size [63].

Larvae that are produced at the end of a fat season are able to obtain a greater share of the food supply. Greater nutrition may enable the pupal stage to end with fertile male and females [60]. Fertile offspring can fly, the main purpose of which is to make breeding between colonies more likely, creating diversity in the gene pool [64]. After the mating flight the newly fertilized queens hibernate during the winter. The
queen starts the colony growth by laying eggs in the spring [60]. Extremely large numbers of virgin queens fly, but their mortality rate is high. In nests with a very large population, it is possible for 100,000 queens to be released within a hour [63]. A few queens are accepted back into the nest after being mated. Those queens are more likely to be those who are sent out to form branch nests [63]. Only a very few queens are successful in establishing a colony. In one study, 1000 incepting colonies were counted at the start of a summer. At the end of the summer, none survived [64].

The mating flight is triggered by the males when their sexual development is complete. When the mating season starts, males randomly go outside on the surface of the nest. When they are outside, they emit an attractor pheromone. With time, the action of the pheromone synchronizes the times when the males go outside to sun themselves. When enough males are outside, the high concentration of the pheromone triggers the mating flight. The new queens follow soon after the males start the mating flight.

In an established colony, the winter phase is different from that of a founding nest. The queens and the repletes retreat to the lower levels of the nest and drop their metabolism to virtually zero. The workers move lower in the nest too. However, they are positioned high enough in the nest that if the temperatures are high enough, they are able to go outside to forage.

In the spring, the temperature rise causes ants to migrate outside the nest, awakening the metabolism of the queens and the repletes. When the colony is completely awake and functioning again, the queen starts the egg laying period.
During the egg laying, the food requirements of the colony are almost completely satisfied by the food drawn from the winter stores. When the eggs laid during the spring mature, they join the foraging force in replenishing the food store for the upcoming winter [63].
7 Simulation

7.1 Introduction

In this section, the hypothesis proposed by the HCC will be tested. A model of the simulation environment is constructed, drawing from the behavior of ants as discussed in the previous chapter. The metrics of the simulation are suggested. The details of the implementation of the simulation are covered. The data from experimental runs is analyzed and discussed.

7.2 Rationale

Just because an idea appears to succeed on paper does not endow the idea with the actuality of working. Nor does it mean that the key features as stated by the author are actually effective. It is inherently difficult to formally analyze the behavior of a model which incorporates many agents, each with incomplete knowledge of the state of other agents. The behavior of the aggregate cannot be predicted without knowledge of individual states of the agents. The simplest method to determine the aggregate behavior from individual states is to create a simulation in which cause follows effect.

7.3 Simulation Design Considerations

One of the advantages of the HCC architecture is that it levels the communication playing field, enabling high-level agents to employ the same state information exchange methods as low-level agents. However, if the simulation is rendered with a large number of highly intelligent agents i.e. large number of possible world state perceptions with fine differences, the results fall into question. Are the actions of the agents the result of the information generated by the HCC architecture, or is it a result of the agent being more
capable of carrying out decisions with a lack of hormonal input? For that reason, the simulation employs a large number of low-level agents. In that manner, it is possible to postulate that the world state model the agent perceives is highly correlated to the internal hormone state of the agent.

Hormones operate in an environment in which multiple tasks are related in a manner that accomplishing the tasks leads to the desired system state. In practice, this could be defined as the generality of the hormone. If the system consists of wildly disparate tasks, or if the hormones are defined so finely that they induce the same result through most of the possible agent state conditions, the HCC architecture is rendered to a complicated method of broadcasting conventional messages, making the concept of hormones redundant. Taking this point of view in account, the HCC architecture would be more effective in systems in which a great percentage of tasks are interrelated. That is, the number of individuals engaged in one task influences the number of individuals engaged in another [65].

For the reasons provided above, it was decided that the best test of the HCC architecture would be simulating ants. The ant model adopted by the simulation differs from living ants. After all, living ants, hormones do not operate outside the body. Individually, ants certainly can't be said to be intelligent. Collectively, however, they are praised again and again in literature for the sheer complexity of global actions they are able to accomplish. Ants also have been exhaustively researched and modeled.
7.4 Properties of Ants

Insect societies have been alluded to being factories within fortresses in that they gather food and raw materials from the outside world, which they employ to maintain their nest, or infrastructure, and their workers [59].

Ants excel supremely in the problem of task division. Ant societies are generally divided in physical castes: queens, drones, and workers. Tasks are also partitioned even further into subtasks. A single ant does not have to accomplish every step of a single task in order for the task to be completed. Other ants can perform the subtasks left unfilled [64]. An individual ant is able to transition between the partitions of multiple tasks as the situation demands. Theraulaz, et al [62] hypothesizes that this behavior is the result of a stimuli-response threshold activation.

7.5 Objectives

The intention of this simulation is not to reproduce the observed action of living ants. The model to be simulated will not be concerned with fine details, i.e. the exact process by which the agent walks or bestowing it with appendages with which it must grasp objects. Such detail is not necessary for showing the viability of the HCC architecture. Rather, such low-level behavior will be achieved transparently. This section explores the intentions of the simulation and the manner of verification.

7.5.1 Emergence

In this paper, emergence has been defined as global level result not specifically encoded for in local rules, but nevertheless emerges as a result of local interactions. However, Assad and Packard [66] argue that emergence can be defined on a scale, based
on the means by which emergence develops. A system is weakly emergent if the global actions are not immediately obvious from the local rules. However, the manner of emergence can be deduced by observing the system in action. If the global behavior is impossible to elucidate from the local rules, a system is considered to be maximally emergent. They, and Darley [67] argue that any simulation run on a computer cannot be truly emergent because the nature of a computer. A computer is a machine that operates discretely, performing arithmetic operations on binary strings; it is impossible to create a situation in which the chain between isolated computations and the global result cannot be replicated. Darley [67] developed an expression of degree of emergence. Darley states that there are two ways in which a system can reach a specific state. One is to simulate all the steps. The second is to employ iterative equations to describe the dynamical behavior, with the goal of reducing the number of computations necessary to reach the same state. Thus emergence is the ratio between the number of computations required for the iterative equations and the number of computations to reach the same point, computing all the steps. In an extremely simple, linear system, one equation, with proper parameters is satisfactory to express all the possible states of the system. In this case, the system is not emergent. If the number of iterative computations approaches the number of computations necessary to actually simulate the system, the degree of emergence increases.

In this case, the dynamical equations describing the simulation are dependent on the simulation selected, and there is no intention of deriving those equations. In face of the different definitions of emergence and the lack of means of measuring the emergence
of the system, in this simulation, it will be satisfactory to observe that global level tasks
are being accomplished.

7.5.2 Homeostasis

In the body, the purpose of hormones is to maintain homeostasis, where the
baseline is defined as normal body operation, but may be altered by the influence of the
hypothalamus [13]. The HCC must be able to maintain homeostasis, as defined by the
designer. This definition will be expanded in detail in a later section. In a nutshell, given
an appropriate energy source, the system must be able to balance itself so that it does not
overproduce and annihilate the food source, or under produce and fail to reach the
maximum potential possible. This quality can be deduced by observing the relations
between food reserves of the repletes and the percentage of time in which the ants engage
in work.

7.5.3 Scalability

One of the most important properties of any multi-agent scheme is the degree of
scalability. An optimal architecture would be one that is capable of operating with two to
an infinite number of agents. This is tested in this simulation by allowing the ant colony
to breed. As the number of agents increase, the system should not break down. Also, the
communication aspect of the HCC architecture is expected to be more effective as the
number of ants increase because the density of agents in a communication area increase,
thus each hormone transmitted will have more impact.
7.6 Ant Model

The basis of the simulation model is described in the chapter on ants. The material covered there is not reviewed extensively. Here, the specific mechanics of the agents in the simulation are discussed. As stated before, there is no intention for actual authenticity.

The majority of the traits shown in the colony are been drawn from wood ants. Also, wood ants have been heavily studied in the literature. However, polydomous species, those that form branching nests generally have an aggregate of more than 100,000 individual ants [63]. Creating a computer simulation than can handle interactions of more than 100,000 individual objects is extremely impractical.

The problem becomes one of compromising between attempting to faithfully model ant behavior and creating a model which satisfies the criteria presented while making it possible to discern the effect of the HCC architecture. One of the major differences between the simulation model and the real-life behavior of ants is the method of communication.

7.6.1 Communication

Ants communicate by three means; tactile, auditory, and phenomenal [64]. Pheromones are the only means of conveying time-independent information [63]. In the simulation model, the tactile and auditory means of communication has been eliminated. Pheromones are replaced entirely by hormones. It is possible to utilize both pheromones and hormones; however that would convolute the influence of the pheromones and hormones, raising questions about the results.
This decision has profound implications because ants survey the land and forage by laying scent trails, however species that rely on seeds, which are scattered individually, rendering scent trails impractical are the exception [64]. The alterations to the model to enable this change are addressed as they appear.

7.6.2 Simulation Environment

The environment in which the agents will interact is made up of a grid. Each square on a grid can be empty, a food source, or a nest. The number of ants allowed to occupy a square is not constrained. Food squares adjust their growth rate based on the season and whether if it draws ants. The behavior of the food supply mirrors that of aphids which have a symbiotic relationship with ants. If ants frequent a food square, the rate at which the food supply grows is increased, up to a point. When the density of a food square passes a threshold, it randomly spawns to neighboring squares. Nests occupy only one square, and can contain an infinite amount of ants. In practice, to conserve the computational resources of the computer running the simulation, a cap is placed on the number of ants that can inhabit a nest.

When an agent broadcasts a hormone, the strength of the signal is inversely proportional to the distance from the originating signal. The dispersion of the signal occurs instantaneously. The duration of the signal is one time step. The signal is transmitted as a property of the square in which it resides in. The signal information in the square contains the signal, its strength, and the vector direction to the originating square.
The property of the square in which an agent resides in is available to the agent as a simple inquiry. This is analogous to the specialized sensors of ants, which allows information to be partitioned in binary sections.

7.6.3 General Characteristics

Agents are independent entities which influence each other by transmitting hormones, and to a lesser extent, by altering the environment through which other agents pass. The agents acquire information about their immediate environment by inquiring the square they are currently residing on. Every agent that ventures outside the nest knows the direction vector back to its nest as well as the vector to the origin of a hormone transmission. This knowledge is maintained by exposure to the queen hormone. If the simulation from the queen hormone dies out, the agent becomes unattached and will wander through the environment until its energy reserves run out, unless it is impressed by a hormone from another nest or colony.

Every agent has an energy storage space and a crop, or a separate energy storage area in their body. When gathering food, agents fill up the crop as much as possible. The energy in the crop is transferred to the active energy space. After the agent reaches the home nest, the energy remaining in the crop is transferred to a replete. If the internal energy reserves fall under a threshold, the agent begs food from any other agent that it encounters. If the other agent has ample energy, it will give some to the begging agent.

The lifespan of an agent is dependent upon the total amount of energy that the agent consumes. When at idle, the agent's energy consumption is at a minimal. When active, consumption is increased greatly. Thus, if an agent remains inside the nest, its
lifespan is significantly longer than that of an agent that is actively working outside the nest. The energy that an agent can put in its active energy store decreases as the agent ages. The agent vanishes if its energy store is zero or its energy storage capability decreases to zero.

The behavior of the agents is regulated by their moods. The mood is established by the season and the hormone or hormone mix that is dominant. Once an agent enters a behavioral state, it persists until the task is complete. When the task is complete, if the triggering hormone is still above the threshold, the agent continues with the current task. Otherwise, it switches to another behavioral state dependent on the hormonal input or reverts to nominal behavior.

In order to differentiate actions of individual agents, elements need to be random. The hormone parameters of individual agents are randomly deviated from a set of initial values. Also, ants walk in a semi-drunk fashion. The ant scans only the squares in front of it, with the direction of scan randomly chosen to be either from left to right or vice versa.

7.6.4 Equilibrium Homeostasis

The agents in the simulation need energy in order to perform. Thus, the relative level of energy is tied to the determination of homeostasis. Ultimately, the actions of the agents revolve around the status of the food reserve of the colony. The demand for food remains constant throughout the seasonal cycle of the simulation. An additional function of a colony is to procreate itself. To address this, the equilibrium state changes
throughout the seasonal year to bring pressure on the agents to perform the necessary actions in order to get the hive ready for procreation and survival.

7.6.5 Castes

The ant model is composed of two castes: Queens and workers. The worker ant can take on six distinct roles: Brood, Old Idle, New Idle, Nurse, Replete, or Food Transporter.

7.6.5.1 Queen

In the simulation, the queen serves as the only agent which is permitted to create new agents. In a more complicated model, the queen can be endowed with a world state model which permits it to weigh the strength of the hormones currently active in the queen and the external environment. With the construction of a complicated model, the queen can gauge when to procreate.

7.6.5.2 Workers:

The workers make up the rest of the population of the agents. The workers select their actions based on a simple stimuli-response threshold. However, for each role, the priority ordering of the stimuli differ. Also, each role has different rules for hormone interaction. The workers take on one of six roles

- Brood
- New Idle
- Old Idle
- Nurse
- Replete
- Food Transporter

**Brood**: When the queen creates new ants, they are initially set to a brood role. If a brood’s energy reserve drops below a threshold, they emit the *food low* hormone, in an attempt to induce other ants to become nurses, or in extreme cases, food transporters. When a brood ant reaches maturity, it transitions to the new idle role. The FSM is shown in (Figure 7-1).

*Figure 7-1. Finite State Diagram for the decision engine of the brood role*
**New Idle:** New idle ants are ants that have transitioned from the brood role. New idle ants are more likely to become nurses or repletes than the old idle ants. The threshold level required to transition to the food transporter role is higher than that of the old idle ants. To maintain a balance between ants that choose to become repletes and those who choose to become nurses, the output gain of the respective hormones is set randomly within a range. The FSM for the new idle role is shown in (Figure 7-2).
Old Idle: The old idle role is acquired only by a transition from a food transporter role. The old idle ants are more sensitive to the food low and food found hormones than new idle ants. It is more energy-efficient to go to a known food location than randomly searching for food, so the decision to transition to the food transporter role is dependant upon the current energy of the ant and its food low output gain parameter.
Thus, only a percentage of the old idle ants make the initial transition to the food transporter role. If they find a food cache, they transmit a *food found*. If the nest is within range, the combination of *food low* and *food found* will trigger the Old Idle to go to the known food location. However, if the *replete* hormone is present, indicating that the food reserves are full. The presence of the *replete* hormone also terminates the *food low* and *food found* that is present in the old idle ant’s internal hormone representation. The FSM is shown in (Figure 7-3)
Figure 7-3. Finite State Diagram for the decision engine of the old idle role
**Nurse:** Those agents are responsible for ensuring that the brood is fed, as well as the queen. They are analogous to living nurses whom reprocess food from the repletes to create a refined form, which they give to the brood and the queen. Once an agent has transitioned into the nurse role, it will remain a nurse till death. The nurse ant is blind and deaf to all hormones, so the FSM is superfluous.

**Replete:** Repletes are agents that stay immobile. They act as food storage containers, containing several times the amount of food any single worker can contain. Food transporter agents give their yield over to repletes when they come in from harvesting. They fill up any agent that comes to it asking for food, with maximum portion size per request. The repletes control the rate and intensity of food harvest by emitting hormones when they run low. The time between hormone transmissions is controlled by the decay rate of the internal hormone, which in turn is controlled by the percentage of energy in the reserves. The setting of those parameters constitutes the homeostatic equilibrium of the system. The FSM is shown in (Figure 7-4)
**Food Transporter:** The food transporter does the bulk of the work. When worker agents are in the food transportation state, they go outside the nest, and if their stored location for food or interest is empty, they search for food randomly. Once they
have seen a food location, they move toward it. If the amount of food in the location exceeds a threshold, the agent creates and transmits a *food found* hormone. If other agents within range are still searching randomly, they will latch on *food found* and head toward its location. When the crop of the food transporter is full, it goes back to the nest to discharge the food to the repletes. If the repletes are full, they transmit a *replete* hormone, which kills the *food low* and *food found* of any idle or food transporter ants. Also, the *replete* hormone triggers the new idle ants to become repletes. In the FSM (Figure 7-5), there is a block giving the food transporter a transition possibility to a beacon role. This is installed for future expansion of the simulation.
Figure 7-5. Finite State Diagram for the decision engine of the food transporter role
7.6.6 Hormones

The intention with hormone design is to be able to minimize the number of hormone groups. Distinctions in responses ideally are dependent upon the modifiers added to the hormone to create isotopes, and their relative strength in the agent’s hormone store, and also the internal rules which dictate the interaction properties of the hormones. In some situations, action is induced if the strength of the hormone, calculated by multiplying the internal hormone strength with an output gain is sufficient, in others, the presence of the hormone is enough. Drawing from the objectives, in the ant simulation model, there are four types of hormones.

7.6.6.1 Food Low Hormone

The \textit{food low} isotope is released by the repletes and the brood. The version that the brood releases has its hops variable set to the maximum in order to prevent it from being propagated. The intention of \textit{food low} is to change the internal world model of the ants to indicate a deviation from homeostasis. The response is generally aimed at recovering food from outside the nest. Specific actions to achieve that task differ slightly from role to role as shown in Figs. 7-2, 3, 4, 5.

7.6.6.2 Food Found Hormone

\textit{Food found} is released by transporters when they come across food caches exceeding a set threshold. The intention of the hormone is to promote efficiency within the ants. \textit{Food found} is ignored by ants that already have a stored food location, but ants that are wandering randomly absorb the hormone by setting its stored food location to that encoded in the hormone.
7.6.6.3 Replete Hormone

The replete hormone is released by food transporter ants that are in the nest and unable to unload the food stored in their crop. The intention of the replete hormone is to show there is a queue of food transporter ants waiting. Food transporter ants searching for food outside will drop their search and return to the nest.

7.6.6.4 Queen Hormone

Only the fertilized matriarch of the nest can emit the queen hormone. This hormone acts as an attractant. If the queen dies, the workers will emigrate and wander randomly till they die or receive a queen hormone which imprints the agent with its home nest location and the identification of the queen.

7.6.7 Hormone Interactions

The queen hormone is the sole exception in that it doesn’t have any interaction rules with the other three. The food low, food found, and the replete hormones interact depending on the role of the agent.

Brood:

- **Replete**: Block production of food low
- **Food Low**: Block production of food low
- **Food Found**: None
New Idle:

- **Replete:** None
- **Food Low:** None
- **Food Found:** None

Old Idle:

- **Replete:** Inactivates *food low*
- **Food Low:** None
- **Food Found:** Active only when *food low* exists

**Nurse:** The nurse role does not respond to any hormones.

**Replete:**

- **Replete:** None
- **Food Low:** None
- **Food Found:** None

**Food Transporter:**

- **Replete:** Inactivate *food low*
- **Food Low:** None
- **Food Found:** If inside, active only if *food low* exists. If outside, active regardless of status of *food low*

7.7 **Simulation**

This section contains the details of the programming the simulation. The simulation programming choices are covered, as well as the model infrastructure, the time resolution, ant motion, setting of the parameters, and how experiments are run.
7.7.1 Programming

Performing a search on the Internet turns up many possible choices of multiagent simulation methods. Swarm [58] was chosen because it is expressly designed for unstructured multiagent experimentation. Swarm is a collection of libraries written in Objective-C which handle the memory tasks and the scheduling of activities. Swarm also allows for a simulation to be seen in a GUI, or run in batch mode without the overhead of redrawing graphics. The simulation is written by using standard tools for memory management, message passing, scheduling, and interactions between the agents and any others.

7.7.2 Model Infrastructure

The Swarm model as programmed is divided in three distinct spaces: AntSpace, where the ants and the nest move about on, FoodSpace, which contains the food values and perform the growing errands for the food, and HormoneSpace, which stores the hormone dispersion pattern for the ants to receive. When an ant passes a hormone to the HormoneSpace for transmission, HormoneSpace handles dispersing the hormone in a circle around the transmitter.

7.7.3 Time resolution

The simulation is run on a computer, thus is composed of discrete steps. The interaction of the ants can not realistically be called completely asynchronous. However, randomness is injected by mixing the order in which the ants take action. In each time step, an ant eats if it needs to, makes one control decision, and moves one square if it chooses to.
The timing of hormone transmission is a problem to be resolved. In an actual situation, when objects operate asynchronously, the ants could be programmed such that any hormone transmission is suppressed if any other ant has transmitted a hormone within a set time of the present. In a discrete simulation, an ant that has its action executed earlier in the list has better chance of its hormone being transmitted. This is resolved by the HormoneSpace as stated earlier. The hormones transmitted over one time step becomes visible to the ants for one time step following transmission.

### 7.7.4 Ant Motion

An ant is aware of the direction in which it is faced. It is also aware of the vector to the home nest and the vector to a food location if one is stored by the ant. In moving, 45 degree error is randomly inserted in the walk. When searching, the ant scans only what is in front of it, preferring the 90 degree cone of what is directly ahead. This increases the likelihood of an ant finding a food store closer than the one it was previously heading to.

### 7.7.5 Parameters

The simulation contains a large number of parameters. In this section, the vital ones are covered.

#### 7.7.5.1 Hormones

The internal representation of a hormone has three parameters:

- Input Gain: Multiplier for incoming hormones, added to the current value of the hormone
- Decay Constant: Constant for linear decay of the hormone strength.
Output Gain: The strength of hormone is multiplied with the output gain to determine priority and/or if the threshold condition is satisfied.

There are four types of hormones in the system. That makes for twelve parameters for each role an ant adopts. The queen adopts one role, and the worker ant adopts six roles. Thus, 84 parameter settings for the hormones have to be considered. However, some hormones have no influence in certain roles. In those cases, the input gain is set equal to zero, preventing the ignored hormone from being created. The decay constant for the ignored hormones are set to the maximum, to flush the ignored hormone within one or two time steps.

In order to introduce a degree of randomness in the control decisions of the ants, their individual settings for the hormone parameters need to be a little different. The simulation sets the maximum allowable variation as percentage deviation from the standard value.

It was arbitrarily decided that hormones are transmitted with an initial strength of one. The maximum internal allowable strength is 10. The following discusses interaction considerations and assigns values to the three parameters of each hormone.

**Brood:**

- **Replete:** Time required to decay is about equal to half of the time required for the brood to mature,

- **Food Low:** Time required to decay is about equal to half of the time required for the brood to mature

- **Food Found:** Ignored
Table 7-1. Hormone Parameters for the Brood Role

<table>
<thead>
<tr>
<th>Hormone</th>
<th>Input Gain</th>
<th>Decay Constant</th>
<th>Output Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replete</td>
<td>1</td>
<td>$\frac{2}{MatureAge} = .05$</td>
<td>1</td>
</tr>
<tr>
<td>Food Low</td>
<td>1</td>
<td>$\frac{2}{MatureAge} = .05$</td>
<td>1</td>
</tr>
<tr>
<td>Food Found</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

New Idle:

- **Replete**: The decay time should be longer than that of the food transporter decay rate for the *replete* hormone so that if the food transporter sends multiple *replete* hormones, the probability that the new idle ant transitions to a replete role is increases.

- **Food Low**: The decay time is longer than that of the *replete* hormone, in order to increase sensitivity to the transmissions of the brood. However, the output gain is low to decrease the probability that the new idle will go outside to look for food.

- **Food Found**: Ignored
Table 7-2. Hormone Parameters for the New Idle Role

<table>
<thead>
<tr>
<th>Hormone</th>
<th>Input Gain</th>
<th>Decay Constant</th>
<th>Output Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replete</td>
<td>1</td>
<td>$\frac{2}{\text{MatureAge}} = .05$</td>
<td>1</td>
</tr>
<tr>
<td>Food Low</td>
<td>1</td>
<td>$\frac{2}{\text{MatureAge}} &gt; .00125$</td>
<td>.3</td>
</tr>
<tr>
<td>Food Found</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Old Idle:

- **Food Low**: Decay time is longer than the decay rate for the *food low* in the replete role to ensure that transmission of *food low* is accumulated.

- **Replete**: The decay time is fast. The new idle have low sensitivity to the *replete* hormone to prevent too many ants from becoming repletes, but if necessary, fast multiple transmissions will trigger a greater percentage of new idle ants to become repletes.

- **Food Found**: *Food found* is not kept long because it is likely that closer ants will have exhausted the resource. The persistence of *food found* is set for the time required to transverse the diameter of a communication area.
<table>
<thead>
<tr>
<th>Hormone</th>
<th>Input Gain</th>
<th>Decay Constant</th>
<th>Output Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replete</td>
<td>1</td>
<td>.5</td>
<td>1</td>
</tr>
<tr>
<td>Food Low</td>
<td>1</td>
<td>$\frac{2}{\text{MatureAge}} &gt; .00125$</td>
<td>1</td>
</tr>
<tr>
<td>Food Found</td>
<td>1</td>
<td>$\frac{1}{\text{CA}_\text{-Radius}} = .0025$</td>
<td>0</td>
</tr>
</tbody>
</table>

**Replete:**

- **Replete**: Fast decay to enable the ant to watch its energy reserve in preparation to transmit *food low* if necessary

- **Food Low**: The initial decay is set long enough for the first ants that went out looking for food to return and possibly stabilize the food reserve. Thereafter, the decay increases inversely proportional to the energy reserves of the replete.

- **Food Found**: Ignored
Table 7-4. Hormone Parameters for the Replete Role

<table>
<thead>
<tr>
<th>Hormone</th>
<th>Input Gain</th>
<th>Decay Constant</th>
<th>Output Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replete</td>
<td>10</td>
<td>.5</td>
<td>1</td>
</tr>
<tr>
<td>Food Low</td>
<td>10</td>
<td>0.0025 (2 - \frac{\text{energyLevel}}{\text{max EnergyLevel}})</td>
<td>1</td>
</tr>
<tr>
<td>Food Found</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

**Food Transporter:**

- **Replete:** If the food transporter is outside, the *replete* hormone is an inductor to go home, so it does not decay until the food transporter enters the nest. When in the nest, the decay rate is relatively fast, allowing time for arriving food transporters to feed the repletes, but fast enough to respond if the reserves of the repletes remain depleted.

- **Food Low:** *Food low* persists long enough for a cursory random search for food

- **Food Found:** With knowledge that other ants may have consumed the food at location given; *food found* persists only long enough to move the diameter of the communication area.
Table 7-5. Hormone Parameters for the Food Transporter Role

<table>
<thead>
<tr>
<th>Hormone</th>
<th>Input Gain</th>
<th>Decay Constant</th>
<th>Output Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replete (inside)</td>
<td>1</td>
<td>$\frac{4}{MatureAge} = .1$</td>
<td>1</td>
</tr>
<tr>
<td>Replete (outside)</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Food Low</td>
<td>1</td>
<td>.0033</td>
<td>1</td>
</tr>
<tr>
<td>Food Found</td>
<td>1</td>
<td>$\frac{1}{2 \cdot CA_{Radius}} = .0025$</td>
<td>1</td>
</tr>
</tbody>
</table>

7.7.5.2 Other Parameters

The setting of parameters other than that controlling the hormones was set with the aim of minimizing the turnover of the ants, to isolate the operation of the hormones in the ants over the long term. Some of those parameters are detailed below.

- **Age:** The maximum age of an ant is set to a value exceeding the length of a simulation. Any ant death will occur because of depletion of energy.

- **Mature Age:** The age at which brood become idle ants – this is set to be short so that ants are available to become food transporters.

- **Birth Rate:** To run the experiments, the ant population is allowed to grow to a desired value, and then held constant. Thus, the birth probability is set so that the growth is large, but not large enough to overwhelm the rate at which food is gathered.
• **Energy Store:** More essential is the ratio of replete storage to that of a worker ant. This controls the percentage of the ants that are repletes, and also changes the decay time between food foraging periods. The ratio was set to 10

### 7.7.6 Experiments

All the random number calls issued by the simulation are handled by a random number generator provided by the Swarm library. Because there is only one random number source, it is sufficient to provide an initial seed to use a different random number stream. The batch mode has command line options to set the number of ants and the variation of the hormone parameters.

Two groups of experiments are performed. In one group, the simulation is allowed to expand to a set number of ants, in the range of 50 to 2000, in increments of 50, and then the queen ant is prevented from creating more ants. The maximum deviation for the hormone parameters is set at 10%. Each set limit is run 20 times. Each run is allowed 100 steps per 10 ants for the growth phase and then run for 100,000 steps. In the other group, the maximum deviation is set at 10% to 100%, with increments of 10%. The number of ants is set at 1000. For each maximum deviation, the experiment is run 10 times.

Data is recorded at every step of the simulation. The following data are recorded:

- Number of brood ants
- Number of idle ants
- Number of replete ants
- Number of nurse ants
- Number of food transporter ants
- Number of changes occurring during the time step
- Number of hormones transmitted during the time step
- Total number of changes since the beginning of the simulation
- Total number of hormones transmitted since the beginning of the simulation
- Average energy of ants
- Number of ants
- Replete energy

7.8 Analysis

The analysis of the data generated by the experiments is split in two partitions. The first partition consists of the period when the ants are expanding toward the set number of ants for the specific experiment. The other partition consists of data that is generated after the set number is reached. The lifespan of an ant is set to be much greater than the time span of the experiment, so after the set number is reached, the individual ants remain roughly the same for the group with the maximum deviation set at 10%. For the group with varying maximum deviation, the population of individual members may change over time. This is discussed in further depth.

7.8.1 Varying number of ants, growing phase

The key analysis parameter is the number of changes to hormones ratio. During the growing phase, the ratio cannot be directly correlated with the number of ants because
the ratio is dependent upon time. A hormone transmission change will not induce a change for at least one step, and may be connected to changes generated up to three steps later. So, the first step is to analyze the growth data to determine if the number of ants is correlated to simulation time. This is shown in (Figure 7-6).

![Graph showing the number of ants versus simulation time](image)

*Figure 7-6. Number of ants versus simulation time*

The maximum spread in the number of ants for any time step is approximately 60. This is small compared to the range over which the experiment was performed, so if only the general trends are looked at, simulation time can be considered parallel to the number of ants. Bearing that in mind, the changes per hormone ratio is shown in (Figure 7-7)
Figure 7-7. Changes per hormone ratio versus simulation time during the growing phase

The initial peak is a result of the first transitions from idle ants to repletes. The first group of repletes are empty of energy, thus transmit hormones more frequently. Also, the initial density of ants in the nest is high, leading to a higher probability that a hormone results in an ant changing its role. That aside, the average of the ratio increases with time. Since time is highly correlated with number of ants, it can be concluded that increasing the number of agents also increases the efficiency of the hormones transmitted.
The intention of the communication and control system is to maintain homeostasis which is defined in this case to be the energy level of the ants. (Figure 7-8) shows the energy of ants, excluding the repletes.

![Figure 7-8. Average energy of ants excluding repletes versus number of ants during the growing phase](image)

In this case, the energy of the ants shows a percentage greater than 100%. This is because the energy as recorded is the sum of the ant internal energy and the energy in its crop. The crop energy is included because if the internal energy of the ant dips below a threshold, it is allowed to draw available energy from its crop. The average is remarkably stable. The negative slope at the end can be attributable to the dwindling
amount of energy available in the simulation; the ants have to search further and longer to be able to harvest enough energy to return to the nest.

The energy balance is also reflected in the amount kept available by the repletes. This is shown in (Figure 7-9).

![Graph](image)

**Figure 7-9. Replete energy versus number of ants during the growing phase**

This figure demonstrates that even though the average energy of the ants decreases, the energy resources of the nest is still ample to meet the needs of the nest.

Looking at the replete energy graph, several explanations as to the decrease in the replete energy can be drawn. In addition to the one already presented, attributing the
decline to the available food supply in the simulation, it is possible that the decrease lies in the hormone transmission decisions of the repletes (or lack thereof). The hormonal activity of the repletes can be inferred by looking at the proportions of the roles of ants within the colony. The percentage of food transporter ants is shown in (Figure 7-10)

![Graph showing percentage of food transporter ants versus number of ants during the growing phase.](image)

**Figure 7-10.** Percentage of food transporter ants versus number of ants during the growing phase

The transition into the role of food transporter is regulated by the replete hormone transmissions. Thus, the increase in the percentage of food transporter ants is a result of an increase in the hormonal activity of the replete ants.
7.8.2 Varying number of ants, fixed phase

In the fixed phase stage, it is assumed that the individual population of ants remains relatively constant. Thus, all statistics are averaged throughout the span from the point where the set number of ants is reached to the end of the experiment. This period encompasses approximately 100,000 time steps.

The changes per hormone ratio is shown in (Figure 7-11)

![Graph showing the average of changes per hormone ratio versus number of ants during the fixed phase](image)

*Figure 7-11. Average of changes per hormone ratio versus number of ants during the fixed phase*

The average of the ratio is higher than that of the growing phase shown in Fig. 7-10 because the data is drawn from the fixed phase part of the experiment. The lower
changes per hormone ratio from the growing phase are not figured into the final calculation. The spread of the ratio over the number of ants are similar, up to a point. As the number of ants becomes larger, it becomes more likely that at any instant, the local density of ants is higher than average, making it more probable that a greater number of ants will be affected by a single hormone.

The energy of the repletes are shown in (Figure 7-12)

![Graph showing average replete energy versus number of ants during the fixed phase.](image)

*Figure 7-12. Average replete energy versus number of ants during the fixed phase*

Combined with the energy of the rest of the ants, as shown in (Figure 7-13), some interesting observations can be made.
Figure 7-13. Average energy of ants excluding repletes versus number of ants during the fixed phase

For one, the energy of the ants appears to follow an asymptotic curve. This assumption can not be extended very far because, as mentioned earlier, the available energy supply in the environment is limited. When the number of ants in the simulation becomes great enough to overwhelm the ability of the environment to regenerate the energy sources, the limit of the curve may as well be zero percent rather than 100 percent as suggested in Fig. 26. The spread in the experimental energy data show that as the number of ants increase, the energy dispersion decreases markedly. Comparing that result with the steadily decreasing energy reserves of the repletes show that at later stages, the ants depend more
on the energy garnered from the repletes rather than being sustained by energy stored in their crop. It is interesting to note, however, that the energy dispersion of the repletes do not appear to narrow. The repletes are well able to provide for the ants, however, with a large number of ants, there is not much excess energy to spare.

Inspecting the composition of food transporter ants in the population gives insight on the control aspect of the repletes. This is shown in (Figure 7-14).

![Figure 7-14](image)

*Figure 7-14. Average percentage of food transporters in population versus number of ants during the fixed phase*

The upward trend in the percentage of the population which is food transporter shows the control influence of the replete ants. As the average energy of the replete decrease, the
more time they spend away from homeostasis. In response, the repletes transmit more control signals in the form of hormones, resulting in a higher average of food transporters over time.

7.8.3 Fixed number of ants, varying deviation during growing phase

This partition of experiments serves to investigate the effect of varying the hormone parameters. The question is whether if the hormones are actually essential to controlling the homeostasis, or if the homeostasis results as a byproduct of the local rules which the ants behave under without hormones.

In the first set of experiments, the growth rate of all of the data sets was constant. Varying the hormone parameters does not give the same result. The growth rate is shown in (Figure 7-15)
Figure 7-15. Average growth rate versus maximum deviation

The birth rate of the queen ant remains the same, so the only explanation for the slowing of the growth rate is that the death rate increases. This is interesting because as long as the ants stay in the nest, and the repletes have energy available, they will not die. Clearly, the ants go out of the nest, and for whatsoever reason, do not come back. Two possibilities exist, that the threshold for the replete hormone in the ant is low and/or the decay constant is high, so when the food transporters in the nest issue the replete hormone, those outside the nest ignore it. Another is that food found is ignored, so the ants continue to search randomly, so extensively that their energy store runs out. One implication of this observation is that, unlike the case of the previous experiments, the
groups of ants with high deviations do not enter a fixed phase. The simulation still cuts off the births when the number of ants reaches 1000, but as the ants die off, the queen will be allowed to give birth to more ants. Thus, the pool of individual ants when the number of ants reaches 1000 is not the same pool as when the simulation is stopped.

If it is the case that the ants are dying because their parameters are such that they ignore hormones, that should be reflected in the changes per hormone ratio. The change in the ratio can be seen in (Figure 7-16)

![Graph](image)

*Figure 7-16. Average of changes per hormone ratio versus maximum deviation during the growing phase*
An unexpected effect is the rise in the ratio at the end. That may be attributable to natural selection; those ants with parameters that are not successful die out while the ants with parameters that are capable of contributing toward the nest survive. However, not all ants with unsatisfactory parameters have the courtesy to leave the nest in a suicide pact. This is shown in (Figure 7-17).

![Figure 7-17. Average percentage of food transporter ants in population versus maximum deviation during the growing phase](image)

The percentage of ants which become food transporters is decreasing. This may indicate that there are idle ants in the hive freelading off the repletes and never become food transporters at all. If this is the case, then the average energy of the ants should be
reduced because the average energy is not as bolstered by ants that forage for food, thereby increasing their energy above 100%. This is borne out in (Figure 7-18)

![Graph showing the average energy of ants excluding repletes versus maximum deviation during the growing phase.]

Figure 7-18. Average energy of ants excluding repletes versus maximum deviation during the growing phase

The question now is whether the decrease in ants capable of becoming useful food transporters affects the replete energy level, thereby the homeostasis of the system. Inspecting the energy level of the repletes in (Figure 7-19)
The energy stored by repletes is more or less consistent. This stands to reason because the initial release of *food low* will be triggered by then replete which is most sensitive to its energy level. The repletes which are insensitive to the *food low* trigger threshold do not interfere with those that are.

### 7.8.4 Fixed number of ants, varying deviation during fixed phase

As stated earlier, the fixed phase at higher deviations is actually not fixed, but analyzing those is interesting because the interval over which the data is averaged is longer than that of the growth phase. Also, it is an instance of evolution occurring, those

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*Figure 7-19. Average replete energy versus maximum deviation during the growing phase*
which are unfit tend to die off, and those which are fit grow in the population over time. The changes per hormone ratio is shown in (Figure 7-20)

![Graph showing changes per hormone ratio versus maximum deviation during the fixed phase](image)

*Figure 7-20. Average of changes per hormone ratio versus maximum deviation during the fixed phase*

The data in the changes per hormone graph is not conclusive because the fitted line is skewed by the wide range present at the 80% point, but it suggests that over time the ratio changes because the ants with parameters that are not successful tend to die off, and ants with a successful set of parameters have a longer lifespan.
If more successful ants tend to survive, this should be shown in the percentage of food transporters. As the successful population increases, the percentage that responds to the trigger to become food transporters should increase. This is shown in (Figure 7-21)

![Figure 7-21. Average percentage of food transporter ants in population versus maximum deviation during the fixed phase](image)

The average energy of the ants should correspond with the percentage of food transporter ants because as the percentage of food transporter ants increases, the likelihood that these ants will successfully forage and receive enough energy to boost their energy above the 100% mark also increases. This is illustrated in (Figure 7-22)
The final inspection is that of homeostasis. The replete energy is shown in (Figure 7-23).
As expected from the discussion on replete energy during the growing phase, the replete energy remains more or less constant.

7.9 Conclusions

Over this chapter, the simulation problem was defined, discussed, and expanded upon. The goal of the simulation was to show that the HCC structure is capable of communication and control. Also, an important criterion was the scalability of the HCC architecture; is it capable of dealing with a wide range of number of agents. Through the analysis, this was proved to the author’s satisfaction.
8 Future Work

8.1 Introduction

This chapter discusses what is possible to further the work on the HCC architecture, both in general and specifically the simulation as presented in Chapter 6.

8.2 HCC Architecture

The HCC architecture has admirably succeeded in the goal of providing a framework for the communication and control of multiagent systems. However, for it to be generally useful, several more points need to be addressed.

The idea of hormones and how they function and interact has been presented. However, the method by which interactions occur has largely been left up to the designer. It would be helpful if classes of interactions are strictly defined. This strict definition is necessary when designing the interface between the hormone system and the control system. As it is, the control system cannot be designed independently of the hormone system. This needs to be accomplished if the HCC architecture is to be employed in a situation where it is desirable to put a team in the field with the flexibility of being able to upgrade it in the future. At present, the workings of the hormonal system must be designed with the control system in mind.

Another large issue is prediction. For the HCC architecture to be effective a designer needs a method by which the results of the interaction of hormone influence the system as a whole. In this thesis, this topic was left untouched because by nature, multiagent systems are highly nonlinear systems. The application of the HCC architecture in the thesis, as exemplified by the ant simulation is relatively simplistic,
with a small number of hormones and limited interactions. The homeostasis was defined to be simple, so predicting the action of the hormones and agents was straightforward. For more complex applications, analytic methods need to be employed before the system is built in order to predict possible problems and formulate solutions.

8.3 Minesweeping Simulation

Further insights may be drawn by further changing the parameters, allowing all 9 available values regulating the hormone characteristics to vary independently. The behavior of the agents are sufficiently constrained such that formal connections between the parameter variation and a criteria of performance may be made. This will be a step toward the direction of fully formalizing the HCC architecture.

8.4 Ant Nest Simulation

The simulation as written is simple, with two classes of ants with one representative of one class, and the rest of the ants composed of the other class. It would serve to illustrate the extensibility of the HCC architecture if another class of ants was added to the system. For instance, some species of biological ants have scouts, ants who specialize in hunting for food and leading workers to the food source from the nest. Other species have transporter ants, those who transport ants between nests as needed. It would be instructive to attempt to integrate new classes of ants while minimizing the changes made to the existing infrastructure.

A raft of assumptions was made regarding the ants' knowledge of the environment. More realistic assumptions as to the ability of the ants to navigate and its
search capabilities would serve to better illustrate the ability of the architecture to work in the real world.

The spot density of ants in the simulation was left unregulated. It is likely that if the density was regulated, the changes per hormone ratio would be affected. Further testing would show if the ratio was geometric in respect to the number of ants, as shown by the data in the simulations or linear.
References


