1.1 Introduction

Observation of the global behaviour of swarming bees or schooling fish calls for some very interesting conclusions. While the group as a whole exhibit some coherent global behaviour, the individual members that form the group are governed by very simple controls. The control "*follow in the direction of your neighbours, but do not bump into them*" could be enough for coherent schooling in fish. The mechanism, by which the global emergent behaviour relates to the simple, limited, unplanned and unreliable individual agent activities, is quite compelling to computer scientists and the research society as a whole.

"....but birds and fish had no leaders.
Their groups weren't organized that way.
Nobody was directing it.
Nor were individual birds genetically programmed for flocking behaviour..."
Michael Crichton, "Prey", 2002.

We explore mechanisms by which large numbers of mobile agents are deployable into an environment and, through local interactions, achieve some specific emergent behaviour. A strategy for achieving desired global behaviours is established. Inspirations from various fields of study such as physics, chemistry, biology, behavioural sciences and computing are considered. Nanotechnology principles are applied as building blocks in system design. Such systems absorb many failures and unplanned behaviour at a lower level without sacrificing task completion [17]. We also take advantage of the uniformity of agent architecture [21]. The validity of our strategy is demonstrated through various simulations.

1.2 The Problem Statement

We seek to establish a generalised strategy for organising swarms of mobile agents into desired emergent behaviour. Our research problem can be rephrased to: *Emergent Behaviour Design Problem.* Understanding the engineering principles for achieving specific emergent behaviour is thus our major concern. We decompose the Emergent Behaviour Design Problem into seven research questions (RQ). Most RQ have sub-questions (SQ) as indicated below.

RQ1: Structural configuration problem.

SQ1-1: Agent construction issue. How do we construct agents?

SQ1-2: Controls. How do we add protocols/rules in agents?

SQ1-3: Emergency: How is emergency achieved from few codes?

RQ2: Interaction mechanism problem

SQ2-1: What interactions dynamics are available to agents?

SQ2-2: What effects does individualism have on agent s?

SQ2-3: How do we achieve agent cooperation?

RQ3: Mobility and directional control problem

SQ3-1: How do we achieve agent mobility?

SQ3-2: How do we achieve directional controls in mobile agents?

SQ3-3: What attracts agents towards a goal?

SQ3-4: What holds the swarm together in a coherent formation?

RQ4: Processing capabilities problem

SQ4-1: What processing ability do agents have?

SQ4-2: How do we achieve cooperative processing?

RQ5: Communication problem

SQ5-1: How is agent communication achieved?

RQ6: Artificial Life simulation problem

SQ6-1: Do agents learn?

RQ7: Environment and the visibility problem

SQ7-1: What relationship exists between agent & environment?

RQ7: Goal search problem

RQ8: Emergent algorithms and the application

SQ8-1: Which behaviour is exhibited from specific controls?

SQ8-2: Which controls influence specific behaviour?

SQ8-3: Why do we need emergent behaviour systems?

SQ8-4: Which emergent behaviour suits specific applications?

SQ8-5: How do we measure and validate emergent behaviour?

RQ9: The generalization problem

SQ9-1: What general principles apply for all designs?

SQ9-2: How do we engineer desired emergent behaviour?

SQ9-3: How do we avoid undesired emergent behaviour?

SQ9-4: What strategy can be prescribed for all perceptions?

Approaches with inspirations from diverse fields of study are explored and used in answering the research questions above.

1.3 Background of the problem

Several approaches for achieving emergent behaviour from swarms of mobile agents have been proposed before [7][21][20][8][14][13][3]. The architectural diversity of these approaches tends to be influenced by differences in fields of study and application area. In later chapters, we will discuss, among others, the physics based approaches [18, 19, 20], chemically inspired approaches [17, 21], biologically and Alife inspired approaches [8,14,13,3].

Nanotechnology is gradually dominating the scientific research society. In recent years, government funded efforts to construct sensor-driven nanorobots have been dramatic [ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ]. Futuristic arguments suggests nanorobots that will cooperatively destroy cancer cells in blood[ ][ ], HIV virus [ ][ ], bird flu, etc. Whilst current concerns are on achieving the construction of the magic nanorobots [ ][ ][ ][ ][ ], we still face the challenge of organising these agents into desired formations. We face the challenge of prescribing a universal approach for achieving emergent behaviour from swarms of mobile nanorobots, regardless of the field of study and application. We seek to integrate various inspirations from diverse fields of studies into a generalised and universal mechanism for achieving emergent behaviour. Our universal mechanism will provide a new paradigm for encoding interaction rules, mobility and directional protocols in nanorobots.

1.4 Research goals

As stated in the previous section, nanotechnology is coming. It is the only world's hope in combating the deadly disease, HIV and AIDS. The construction of nanorobots will soon be achieved [ ][ ]. A universal mechanism for achieving desired emergent behaviour from swarms of mobile nanorobots is required. Our challenge is to comprehensively integrate views from different fields of studies in prescribing a generalised universal mechanism. We also face the challenge of proving the validity of our mechanism in diverse fields. In this research, we seek to *prescribe a mechanism for achieving desired emergent behaviour from swarms of mobile nanorobots*. Eight sub-goals (SG) are suggested in an attempt to achieve the research goal:

SG1: Establish nanorobots design strategies/issues and provide general construction rules.

SG2: Establish agents' interaction dynamics and the art of cooperation

SG3: Establish how agents achieve mobility and directional controls towards a specific goal, maintaining a coherent formation.

SG4: Establish the level of knowledge and processing capabilities required in agents for efficient global formations

SG5: Determine effective communication mechanism between agents

SG6: Establish the level of environment/agent relationships. Explain formations & behaviour under different circumstances.

SG7: Generalise principles and mechanisms on visibility issues

SG8: Indicate potential application areas of the proposed paradigm

The universal mechanism will have an impact in research from diverse fields of studies, where emergent behaviour design is essential.

1.5 Importance of the study

We acknowledge the diversity of fields covered under nanotechnology and emergent behaviour design in general. We also acknowledge tremendous research work in progress on nanotechnology and nanorobots constructions. Futuristic ideas, as already said, suggest technological advances in almost all science, to exponentially grow with the introduction of nanotechnology. Our work comes at the right time, when scientists are barely concerned about nanorobots' control issues, but rather, structural design issues.

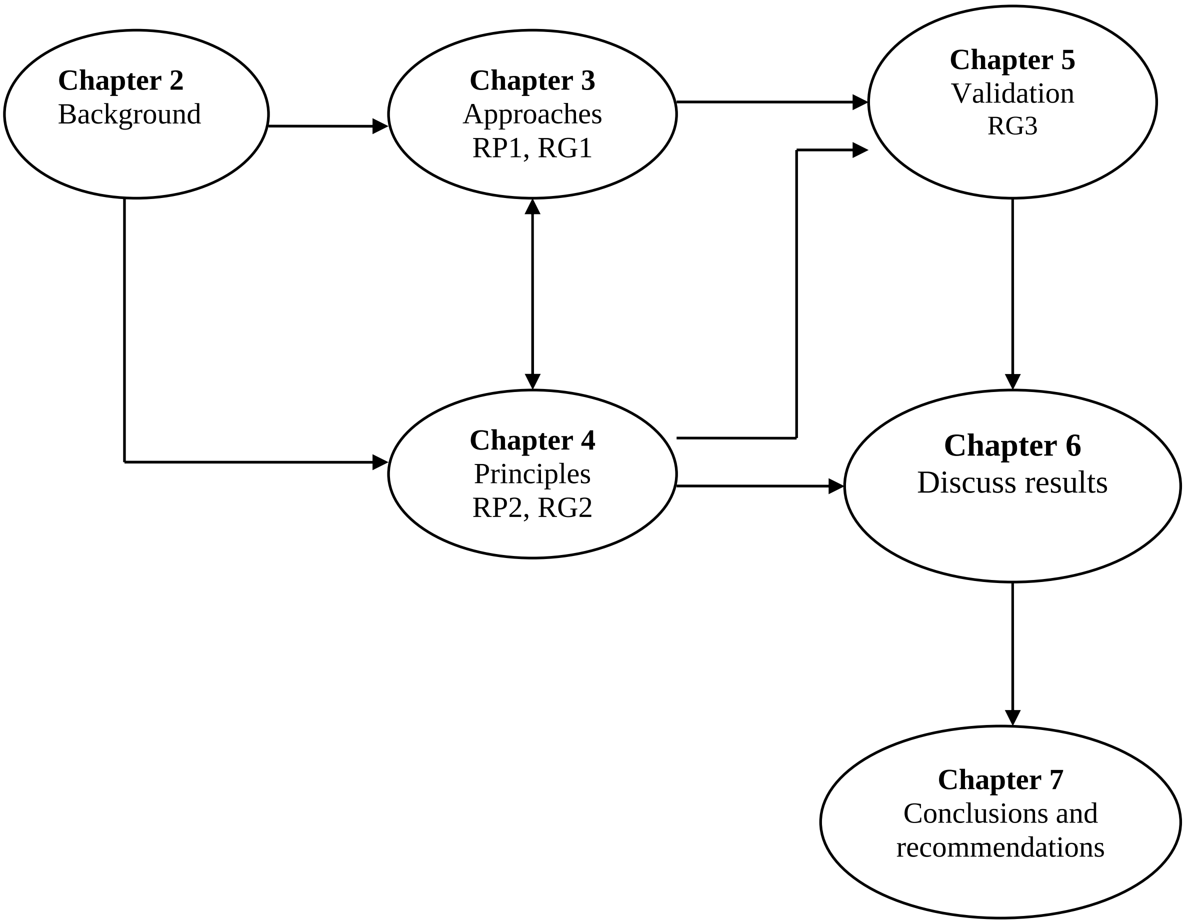
The most useful applications of emergent behaviour design, at nanoscale level remain the medical technology. In this field, nanorobots could be coded to swarm in blood vessels towards cancer-affected cells, or HIV virus engines, before destroying them [ ][ ][ ]. Another potential contribution will be to encode nanorobots to detect toxic chemicals, measure their concentrations in the environment, before neutralising them [21]. Some beliefs suggests that nanorobots will solve the world water shortage problem, geography and agriculture related problems [ ][ ][ ].

Ironically, the theoretical properties of nanorobots are precisely the properties desired for beneficial applications in military sciences, such as nuclear science [ ][ ][ ][ ]. Little is yet known about nanotechnology's potential life and environmental impacts [ ][ ][ ][ ][ ] . This research comes at the time when emergent behaviour design is expected to be the next challenge in nanotechnology advances.

1.6 Structure of the thesis

We provide a synopsis of each chapter. The research problems addressed and research goals achieved in each chapter are described where applicable. Figure 2 below shows the relationships and dependencies between chapters and how each chapter contributes towards the solution of the research problem and the subsequent achievement of the goals. Chapter 2 provides a detailed discussion of

Figure 2



related literature. We discuss current research projects in emergent behaviour design. The research discussed in this chapter forms the theoretical basis of chapters 3 and 4. In Chapter 3, we scrutinize the different approaches used in emergent behaviour design. We address RP1 to achieve RG1. In Chapter 4, we establish generalised principles based on literature from chapter 2 and approaches discussed in chapter 3. A generalised mechanism for achieving global behaviour is presented. In Chapter 5, we verify the validity of the established mechanism through simulations and experiments. The infrastructure module for verifying the principles is described. The established mechanism and principles are consolidated through tests and experiments. A general algorithmic framework for achieving desired emergent behaviour is prescribed. We address RP2 and achieve both RG2 and RG3. Chapter 6 discusses and analyses the results obtained in chapter 5. We provide the answer to the Emergent Behaviour Design Problem. Chapter 7 summarises the contributions of this thesis. We also suggest some areas for future work.

1.7 Scope of study

1.8 Conclusion

We defined our problem statement. The background to the problem statement was provided. Our research goal was stated and further decomposed into eight sub-goals. We also highlighted the importance of this research both to the body of knowledge and the society at large. The structure of the whole thesis followed, where we explained what each one of the later chapters would discuss. We concluded the chapter by providing the scope of our research. The next chapter will provide literature on related work.