

Master's Degree in Computer Science and Engineering

Unity for Collektive: Reducing Reality Gap in the Simulation of Collective Adaptive Systems

Thesis in:
SOFTWARE PROCESS ENGINEERING

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Abstract

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Contents

Abstract	iii
1 Introduction	1
1.1 Motivation: Swarm Behaviour	2
1.2 Problem Statement: Engineering Challenges in Simulation	3
1.3 Contributions	3
1.3.1 A Standardized Automation Workflow for Unity Packages .	3
1.3.2 A 3D Aggregate Computing Simulator	3
2 Background and State of the Art	5
2.1 Distributed Systems and Organizational Complexity	5
2.2 Self-Organizing Frameworks	5
2.2.1 Aggregate Computing	5
2.3 Simulation Landscape	5
2.3.1 Paradigms	5
2.3.2 The Reality Gap	5
2.3.3 Realism vs. Scalability	5
2.4 Game Engines as Simulators	5
3 Unity-Package-Template: Automated Unity Development Infrastructure	7
3.1 Requirements	7
3.2 Features	7
4 Collektive×Unity: Designing a 3D Simulator for Collective Systems	9
4.1 Goal	9
4.2 Requirements	9
4.3 Architecture	9

CONTENTS

5 Implementation of Collektive×Unity	11
5.1 Design	11
5.2 Implementation Details	11
6 Case Study: Environment-aware Gradient Ascent	13
7 Results	15
7.1 Comparison with Socket-based Communication	15
8 Conclusions and Future Work	17
Bibliography	19

List of Figures

LIST OF FIGURES

List of Listings

LIST OF LISTINGS

Chapter 1

Introduction

Modern computing is moving away from the era of powerful and isolated machines toward one composed by massively interconnected ensembles of devices. We can observe this transition everywhere, from global Internet of Thing (IoT) sensor networks to smart city infrastructures. In such scenarios, the focus shifts from ‘how to compute’ to ‘how to coordinate’.

As the number of devices in these systems grows into the thousands or millions, traditional centralized management becomes a bottleneck. The latency, bandwidth constraints, and single-point-of-failure risks of a ‘command-and-control’ architecture make it unsuitable for the dynamic, often unpredictable environments these systems inhabit. Instead, we must look toward decentralized coordination, where collective intelligence arises from local interactions rather than global oversight.

This thesis explores the intersection of high-level collective programming and high-fidelity simulation. Specifically, it addresses the engineering gap between abstract coordination models, such as Aggregate Computing (AC), and the practical requirements of developing, testing, and deploying these models within realistic 3D environments. By leveraging the power of modern game engines and automated development workflows, this work aims to provide a robust infrastructure for the next generation of collective system design.

1.1 Motivation: Swarm Behaviour

The natural world provides the strongest precedence for the goal of resilient decentralized coordination. From the coordinated flashing of fireflies to the intricate architectural achievements of termite mounds and the smooth collective motion of starling murmurings, biological systems exhibit an efficiency that is frequently difficult for classical engineering to match. These phenomena, which are collectively referred to as Swarm Intelligence (SI), arise from the interaction of many simple agents that follow localized rules rather than from a global supervisor.

In a natural swarm, intelligence is inherently distributed and emergent. Individual agents (be they ants, bees or birds) possess only a partial perception of their surroundings. The collective however can solve high-order problems such as finding the shortest path to a food source or executing rapid evasive maneuvers against predators. From an engineering perspective, these systems offer three indispensable properties:

- the absence of a central controller; the loss of individual units does not compromise the mission.
- The logic governing ten agents often remains functional for ten thousand, as interactions remain local regardless of total population size.
- Swarms autonomously adapt to dynamic environments, re-configuring their behaviour in response to external stimuli.

As we attempt to port these characteristics into the digital and physical domains (specifically through paradigms like AC) we face a significant translation gap. While the mathematical models for collective logic are maturing, the infrastructure to test them in realistic, high-fidelity environments remains fragmented. To truly harness the potential of swarm behaviour in human-made systems, we must develop tools that can simulate the complex interplay between decentralized algorithms and the physical world.

1.2. PROBLEM STATEMENT: ENGINEERING CHALLANGES IN SIMULATION

1.2 Problem Statement: Engineering Challanges in Simulation

Simulation has been widely explored in terms of scalability, but not many experiments have been done regarding high-fidelity. This field brings into play hard constraints that mathematical rigor often does not consider. Physics collisions, gravity, and friction are just examples of what a good high-fidelity simulator could add to a cooperative swarm simulation. It is quite intuitive why no one wants this burden: it is a massive implementation that would take years to see the light. Fortunately, game engines do this work for us; they add physics engines capable of computing the results of physical interactions with rigor. The real problem now becomes only one: bridging those two worlds.

1.3 Contributions

1.3.1 A Standardized Automation Workflow for Unity Packages

1.3.2 A 3D Aggregate Computing Simulator

1.3. CONTRIBUTIONS

Chapter 2

Background and State of the Art

2.1 Distributed Systems and Organizational Complexity

2.2 Self-Organizing Frameworks

2.2.1 Aggregate Computing

2.3 Simulation Landscape

2.3.1 Paradigms

2.3.2 The Reality Gap

2.3.3 Reéalism vs. Scalability

2.4 Game Engines as Simulators

Chapter 3

Unity-Package-Template: Automated Unity Development Infrastructure

3.1 Requirements

3.2 Features

Chapter 4

Collektive \times Unity: Designing a 3D Simulator for Collective Systems

4.1 Goal

4.2 Requirements

4.3 Architecture

Chapter 5

Implementation of Collektive×Unity

5.1 Design

5.2 Implementation Details

Chapter 6

Case Study: Environment-aware Gradient Ascent

Chapter 7

Results

7.1 Comparison with Socket-based Communication

Chapter 8

Conclusions and Future Work

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