

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

Supervisor
Prof. Danilo Pianini

Candidate
Filippo Gurioli

Co-supervisors
Martina Baiardi
Angela Cortecchia

Graduation Session: IV
Academic Year 2024-2025

Abstract

Max 2000 characters, strict.

To my grandparents and Roberto...

Contents

Abstract	iii
1 Introduction	1
1.1 Motivation: Swarm Behaviour	2
1.2 Problem Statement: Engineering Challenges in Simulation	3
2 Background and State of the Art	5
2.1 Distributed Systems and Organizational Complexity	6
2.2 Self-Organizing Frameworks	6
2.2.1 Aggregate Computing	6
2.3 Simulation Landscape	6
2.3.1 Paradigms	6
2.3.2 The Reality Gap	6
2.3.3 Realism vs. Scalability	6
2.4 Game Engines as Simulators	6
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
4.2.1 Business Requirements	9
4.2.2 Domain Requirements	10
4.2.3 Functional Requirements	11
4.2.4 Non-Functional Requirements	12
4.3 Architecture	12
4.3.1 Collektive Parser	12

CONTENTS

5 Implementation of Collektive×Unity	15
5.1 Design	15
5.2 Implementation Details	15
6 Case Study: Environment-aware Gradient Ascent	17
7 Results	19
7.1 Comparison with Socket-based Communication	19
8 Conclusions and Future Work	21
Bibliography	23

List of Figures

4.1 Diagram showing the bidirectional communication bridge between Unity and Collektive.	13
--------------------------------------------------------------------------------------------------	----

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 cro:IoTInternet 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 cro:ACAggregate 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 *cro:SiSwarm* 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 Challenges in Simulation

Simulation has been widely explored in terms of scalability, but not many researches 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. Traditional simulators often prioritize the number of agents at the expense of environmental complexity, leading to a ‘reality gap’ that complicates the deployment of algorithms onto physical hardware. Fortunately, game engines do this work for us; they add physics engines capable of computing the result of physical interactions with rigor. The real problem now becomes only one: bridging these two worlds.

The challenge of bridging high-level coordination with game-engine-driven physics is not merely a matter of data transfer, but one of architectural alignment. In particular:

- synchronism: collective programming models rely on discrete logical steps whereas game engines operate on a continuous, high-frequency tick (e.g. 60Hz, 60 frames per second).
- Abstraction: collective models treat agents like points in space whereas high-fidelity environment represent them as complex entities with mass, inertia and physical bounds.
- Scalability: the simulator should still be able to compete with other collective programming simulators in terms of nodes represented inside the experiments and their interactions.

1.2. PROBLEM STATEMENT: ENGINEERING CHALLANGES IN SIMULATION

Chapter 2

Background and State of the Art

To contextualize the contributions of this thesis, it is necessary to establish the theoretical foundations upon which it is built. This chapter explores the evolution of distributed systems toward collective intelligence and examines the formalisms of self-organizing frameworks. By evaluating the limitations of current simulators, this chapter identifies the technical ‘reality gap’ that this research aims to bridge, providing the necessary background to appreciate the integration of high-fidelity game engines into the decentralized coordination workflow.

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 Reealism 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×Unity: Designing a 3D Simulator for Collective Systems

This chapter face the core research project produced for this thesis: a simulator for 3D complex Adaptive Systems (CAS).

4.1 Goal

The project goal is to bridge the Unity game engine with the aggregate computing library named Collektive.

This communication should be bidirectional, achieve high performance and enable huge customization.

4.2 Requirements

Requirements are splitted into separated categories.

4.2.1 Business Requirements

- The project should create a communication channel between the Collektive back-end and the Unity front-end.

- The project should grasp information from Unity node sensors and share them to the Collektive program.
- The integration must map the output of the Collektive aggregate program to Unity Actuators (e.g., changing position, color, or state of a GameObject).
- The system shall evaluate and implement a low-latency cross-IPC inter-process communication (IPC) or bridge mechanism to minimize overhead between the JVM-based Collektive and the C#-based Unity environment.
- The integration should allow Collektive nodes to perceive Unity's colliders, rigidbodies and spatial triggers as first-class citizens.
- The integration layer should remain agnostic to the specific CAS case study.

4.2.2 Domain Requirements

Simulator Domain

- The simulator should have customizable node sensors.
- The simulator should have customizable node actuators.
- The simulator should have customizable step duration (i.e. *delta time*).
- The simulator should be able to pause the simulation.
- The simulator should have a centered handling of randomization to enable reproducibility.
- The simulator should support addition and remotion of nodes in the simulation dynamically.
- The simulator should allow nodes to interact at least with the following Unity components:
 - rigid body
 - collider

4.2. REQUIREMENTS

- The simulator should support addition and remotion of neighbors dynamically.
- The simulator should support any kind of neighborhood discovery.

Communication Domain

- The communication should follow the reactive pattern (i.e. Collektive reacts to Unity's stimuli).
- The data exchanged should be agnostic from the underlying case study.
- Performance should be the driver for choosing the right technology.

Research Domain

- The system should prove the feasibility of integrating game engines within CAS frameworks.

4.2.3 Functional Requirements

User Functional Requirements

- The user should treat a Unity scene as the simulation environment.
- The user should treat the Unity Editor as the simulator.
- The user should be able to add and remove nodes from the environment.
- The user should be able to create neighborhood discovery logic.
- The user should be able to inject any kind of collektive program inside the simulation.
- The user should be able to attach many different sensors and actuators to the same node.
- The user should be able to configure each node independently from the others.

System Functional Requirements

- The system should allow users to define custom sensors and actuators without modifying the core integration library.
- The system should allow users to define custom Collektive program without modifying the core integration library.

4.2.4 Non-Functional Requirements

- The system should maintain stable frame rate (> 30 FPS) with at least 500 active collektive nodes in a low budget laptop (ryzen 7 5700U, 16GB DDR4, integrated GPU).
- The system should be implemented with the fastest technology found during exploration.

4.3 Architecture

The integration is designed as a modular bridge between Unity and Collektive, facilitating the bidirectional flow of information as illustrated in diagram 4.1. The bridge architecture is decomposed into three distinct functional components:

- Unity Parser: Responsible for translating the 3D environment's state into a language-agnostic representation.
- Collektive Parser: Serves to map the aggregate logic and state transitions from the Kotlin-based library into actionable commands.
- Core Bridge: The central orchestrator that synchronizes these two domains.

4.3.1 Collektive Parser

To enable communication across a network or IPC layer, the Collektive API! requires a robust serialization strategy. Two primary design choices were made to facilitate this:

4.3. ARCHITECTURE

- the simulation runs on a single machine; thus, Collektive is configured as InMemory to minimize communication latency;
- the generic identifier in Collektive has been reified to an integer to ensure predictable serialization.

The primary challenge lies in the program’s input and output, which are both generics. While maintaining these as generics is essential for flexible collective behavior, it complicates data exchange. Rather than the brittle approach of manually replicating data structures and custom serializers on both sides of the bridge, this implementation adopts an IDLInterface Definition Language (IDL). By utilizing an IDL, the system decouples the data definition from the implementation language, allowing ‘a program or object written in one language [to] communicate with another program written in an unknown language’ [Wik].



Figure 4.1: Diagram showing the bidirectional communication bridge between Unity and Collektive.

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

Bibliography

[Wik] Wikipedia. Interface description language.

BIBLIOGRAPHY

Acknowledgements

Optional. Max 1 page.