

Sensing Emergence in Complex Systems

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Abstract—We propose the Sensing of Emergent behavior in a Complex Adaptive System (SECAS), as an extension of our previous work Formal Agent-Based Simulation Framework (FABS). Using aggregated data from an array of proximity sensors, SECAS allows for the detection of complex behavior such as flocking of mobile robots or life forms. For validation, we develop an agent-based simulation model. Extensive simulation experiments using a wide range of randomly deployed sensors demonstrate the effectiveness of SECAS in the sensing of flocking.

Index Terms—Agent-based simulation, cognitive sensor networks, complex adaptive system (cas), environment, event detection, flocking, multiagent systems.

I. INTRODUCTION

COMPLEX ADAPTIVE SYSTEMS (cas) are known to exhibit discernable global patterns termed as “emergence” [1]. These patterns emerge as a result of nonlinear interactions of numerous components of the cas. Traditionally, emergent behavior has been considered to be detectable by intelligent observers [2]. With the recent advances in sensors, it seems appropriate to explore how seemingly simple sensors might be useful in the detection of such intelligent behavior.

Agent-based modeling has previously been shown to be the prime choice for modeling and simulation of complex and self-organizing systems such as in the domain of sensor-based, P2P and ad-hoc networks [3].

Emergent behavior has traditionally been considered difficult to define and hard to detect. Boschetti and Gray [2] describe three levels of emergence.

- 1) Pattern Formation and detection such as oscillating reactions, etc.
- 2) Intrinsic Emergence such as flocking behavior.
- 3) Causal Emergence such as human behavior using messaging.

In our previous paper [4], we proposed a Formal Agent-Based Simulation Framework (FABS), a formal specification framework coupled with an agent-based model for modeling and simulation of sensing in a complex environment. In FABS, the goal was to couple the application of an ISO standard formal specification language “Z” with the development of an agent-based model of sensors. FABS, however, was neither concerned with empirical results nor specified any rules for sensing emergence. In this letter, we extend FABS by proposing Sensing of Emergence in Complex Adaptive Systems (SECAS). SECAS utilizes

aggregate data from a randomly deployed sensor array to sense “emergent” flocking behavior [5] of “boids”¹ in an environment.

The rest of this paper is organized as follows.

We first describe formal methodological development followed by a discussion of the simulation experiments and results. Finally, we conclude this paper.

II. METHODOLOGY

SECAS is based on the use of a distributed set of sensors to collectively sense complex behavior. The basic hypothesis can thus be defined as follows.

A. Definition 1

Emergent behavior can be perceived, granted if it is associated, first, with an environmental change, which can be “Sensed” and second, the values can somehow be used in an aggregation function reflecting the emergent effect as a manifestation of the global environmental change.

In the chosen example of flocking, we note that the complex flocking phenomenon requires the “boids” to come closer, while moving in a seemingly unconstrained fashion. Flocking boids come closer to each other without jumbling together. To sense this complex behavior, we note that intuitively, the lower the total number of “proximity” sensors that would turn on (being in the vicinity of boids), the more the emergent flocking behavior would be deemed to have occurred. Thus, our proposed SECAS rule for the “flocking world” can be stated as follows.

B. Definition 2

In a contained but unconstrained world with an array of proximity sensors, the emergent flocking behavior of boids can be detected by the examination of aggregation trends in historical data collected from the sensors.

C. Measurements

The key measurement in SECAS is “Sensed” (represented by $S(t)$), the mathematical aggregation (sum) of measurements of all sensors at any given time t . So, every time a sensor turns on, it is considered to add to the Sensed value. Thus, Sensed would always be less than or equal to the total number of available sensors in the world at that instance ($N_s(t)$) as shown in (1.1)

$$S(t) \leq N_s(t). \quad (1.1)$$

If $n_d(t)$ represents a single sensor which is detecting “boids” in its proximity, from a total of i active sensors at a given time, $S(t)$ being the sum of values of all proximity sensors, turning on, would thus be formally defined as follows:

$$S(t) = \sum_{d=0}^{d=i} n_d(t). \quad (1.2)$$

¹Boids is a general term that can be applied to entities ranging from a group of mobile robots to intelligent life forms such as insects, birds, or fish.

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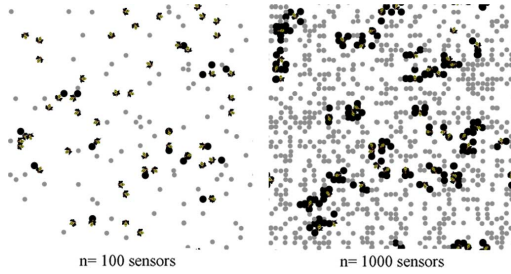


Fig. 1. Simulation experiments with varying numbers of sensors.

III. SIMULATION EXPERIMENTS

In this section, we first discuss the experimental setup for the simulation experiments followed by a discussion of results.

A. Experimental Setup

Following previous work on the simulation of flocking behavior, the simulated world is assumed to be “toroidal.” Toroidal worlds enable the boids to move in an unconstrained manner while still allowing the sensors to observe them. Sensors are considered to be low-power consuming devices such as those based on [6] and capable of detection of presence of boids, e.g., using infra-red sensing. When “boids” come in the vicinity of a sensor, the sensor is visualized with an increase in the size of the sensor, as shown in Fig. 1.

B. Description of Experiment Sets

To eliminate the possible effects of random behavior, each simulation was executed ten times. Each individual experiment continued for 1000 steps. Summarized simulation results are subsequently plotted using high-low graphs in a 95% Confidence Interval.

1) *Experiment Set I:* In the first experiment set, the number of boids was set to a constant (50), while the number of sensors was varied from 100 to 1000 sensors, as shown in Fig. 1.

2) *Experiment Set II:* The second experiment set was a validation exercise. It was used to evaluate the effects of varying the number of boids in the flocking world on the effectiveness of using *Sensed* as a means of detecting flocking. Here, the number of sensors was set as a constant (1000), while the number of boids was varied from 50 to 450 boids.

C. Discussion of Results

Results of Experiment set I can be observed in Fig. 2. Here, as flocking takes place, the *Sensed* value is minimized gradually. The effectiveness of SECAS can be seen since similar results can be observed even when sensors are varied from 1000 to 100 sensors, whereas in Experiment set II varying the number of boids does not have any significant effect on the detection of flocking. Thus, a smaller number of boids in the environment can still be detected using SECAS (by using the *Sensed* value) with the same precision as a larger number of boids, as shown in Fig. 3. Thus, empirical results obtained by performing numerous experiments demonstrate the effectiveness of SECAS in a variety of scenarios.

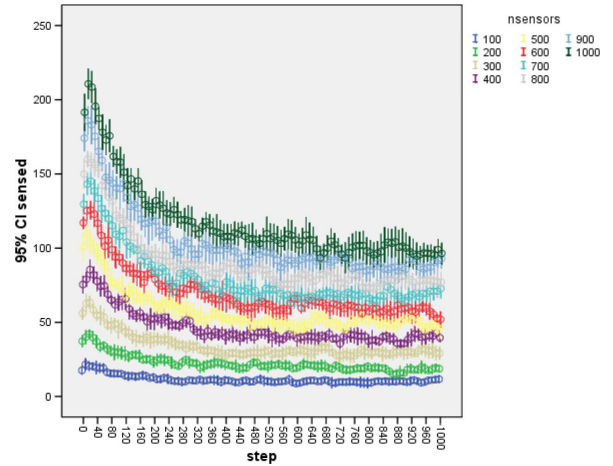


Fig. 2. Ninety-five percent CI-based value of *Sensed*.

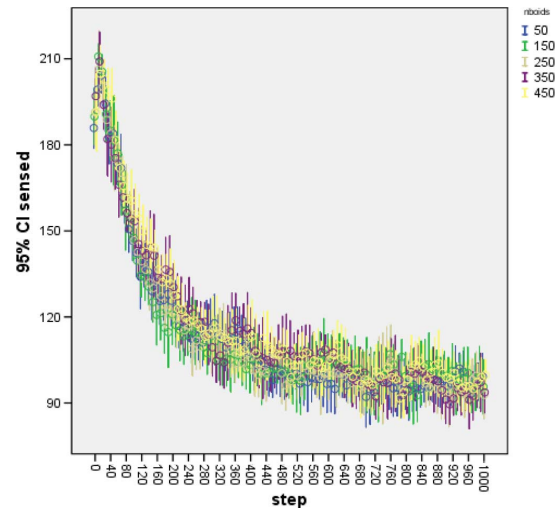


Fig. 3. Ninety-five percent CI value of *Sensed*, while varying the number of boids.

IV. CONCLUSION AND FUTURE WORK

In this paper, we have proposed SECAS for the detection of emergent behavior in the vicinity of randomly deployed sensors. Our extensive simulation experiments validate the effectiveness of SECAS in detecting emergent behavior, in general, and flocking behavior, in particular. In the future, we hope to extend SECAS in the domain of other emergent phenomena in various types of cas.

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