Entropy and Self-Organization in Multi-Agent Systems

CSCE 990 Seminar
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Citation of the Article


193 citations.
Outline

• Introduction
• Motivation
• An entropy model for self-organization
• Experimental setup
• Results and discussion
• Summary
• Praises
• Critiques
• Relationship with class project
Entropy and 2\textsuperscript{nd} law of thermodynamics

- Movie clip of “the fabric of the cosmos”
- Entropy
  \[ S = k_B \ln W = -k_B \sum_i P_i \ln P_i \]
- 2\textsuperscript{nd} law: entropy of an isolated system never decreases.
  = isolated systems spontaneously evolve towards the state of maximum entropy.
- The world tends to disorder (entropy increase).
  \textit{Murphy’s law: Anything can go wrong will go wrong.}
- Organized structure can be achieved only through hard work (entropy decrease).
Self-organization in MAS contradict 2\textsuperscript{nd} law of thermodynamics?

- Examples: insect colonies, human culture
- Individual autonomy + global order
  - individual autonomy of agents spontaneously leads to organized structure (lower entropy).
- Paradox: contradiction of 2\textsuperscript{nd} law of thermodynamics?
- Not really!!!

<table>
<thead>
<tr>
<th>Thermodynamics system</th>
<th>Multi-agent system</th>
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</thead>
<tbody>
<tr>
<td>Adding energy</td>
<td>Adding information</td>
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Global order
Self-organization in MAS contradict 2\textsuperscript{nd} law of thermodynamics?

- The set of agents looks like an isolated system, but it is not!!!
- The isolated system is composed of the set of agents and the dynamic information around them, such as pheromone.
- The source (pheromone deposit) of dynamic information is created by agents themselves.
- Agents react to the dynamic information to self-assemble.
- The entropy increase of dynamic information is sufficient to cover the entropy decrease from the self-organizing process of agents. The total entropy goes up !!!
Objectives

- Link self-organization in MAS to thermodynamics concepts.
- Provide a measure for the behavior of MAS.
Kugler-Turvey model suggests multiple coupled levels of dynamic activity.

- Macro level: self-organizing behavior
- Micro level: dynamics generate increasing disorder
- As a whole: increasingly disordered over time
An example: pheromone

• Scent markers for
  
a) recording states
  
b) directing movements

• Three information-processing functions of pheromone field
  
a) aggregates pheromone deposits
  
b) evaporates pheromones over time
  
c) disseminating information
The model in detail
## Information entropy

<table>
<thead>
<tr>
<th></th>
<th>Thermodynamics</th>
<th>Information</th>
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<tbody>
<tr>
<td>Micro level</td>
<td>$S = k_B \ln W$</td>
<td></td>
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<tr>
<td>Macro level</td>
<td>$dS = dQ / T$</td>
<td>$S = -\sum_i P_i \ln P_i$</td>
</tr>
</tbody>
</table>

*$W, B, k, T, dQ, dS, P, i$
Experimental setup – coordination problem

- Destination release one pheromone molecule (PM) at each time step.
- PM moves a distance of 2 every time step.
- Walker moves a distance of 1 every 5 time steps.
- Overall, PM moves 10 times faster than walker.
Movements of walker and pheromone molecules

Exploitation

\[ |\vec{G}| = \sum_{r_i < \rho} \frac{g}{r_i^2} \]

Exploration

random vector \( \vec{R} \)
Measuring entropy

- Measuring number of system states
- Measuring the probabilities
Measuring number of system states

Location based gridding
$n \times n$ grids, $m$ particles
state count: $n^{2m}$

Direction based gridding
$n$ - rayed stars, $m$ particles
state count: $nm$
Measuring probabilities

• Analytical approach – impractical

• Monte Carlo approach: count number of replications for states, 30 replications in total at each time step. Entropy is normalized to be $[0, 1]$.
  Example, throw a die.
Results – entropy in the micro system (pheromone)

Locational entropy using a $5 \times 5$ grids
Directional entropy follows similar pattern
Walker path: unguided vs guided

Unguided

guided

\( \rho = 20, \quad \bar{R} = 0 \)
Ensemble of guided walkers

\( \rho = 20, \ \bar{R} = 0 \)
Macro level: locational entropy - unguided vs guided

Guided walker
- locational entropy (15 × 15 grids)
  - median distance to target
  - median visible molecules
Macro level: directional entropy - guided

- directional entropy (15 × 15 grids)
  - median distance to target
  - median visible molecules
Entropy in the overall system

Entropy gain at micro level

Entropy loss at macro level
Summary

• Concepts from thermodynamics were invoked metaphorically to explain the self-organization in MAS.

• Quantified this metaphor through simple partitioning methods and MC simulations.

• Coupling of self-organizing process at the macro level with an entropy-increasing process at a micro level.

• Some form of pheromone or currency is the underlying mechanism for creating an entropy-increasing process.
Praises

- Multidiscipline knowledge and insightful observation of the metaphor.

- Simple but powerful design of the multi-layer model and entropy quantification.

- Effective communication of the concepts and results.
Critiques

- An exploration term was defined, but never used. (\(\vec{R} = 0\) all the time)

- The number of replicates (only 30) was low considering the huge amount of the possible states.

- Pheromone agents were added arbitrarily. How multiple walker agents interact through the pheromone field created by themselves?

- Limitations? Energy-based approach rather than entropy-based approach?
Relation to the class project

• Class project: *Multiagent Cooperative Payload Transportation with Modular Self-reconfigurable Robots*

• Load-carrying agents directly interact with neighbors, not through pheromone field.

• Path can be lead by the pheromone field. Scout agent?
Questions?