Stochastic assembly: a puzzle test-case

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1 Problem description

1.1 Complex System Modulation problem (Loïc's thesis)

Consider an intrinsic complex system with observable dynamics and a measurable performance metric. Let this intrinsic system attains an optimal performance metric value X_{opt}. Introduce agents into the system with designed specific behaviors, getting an augmented system. Can we design such behaviors so that the performance metric of the augmented system attains an optimal value Y_{opt}, with $Y_{opt} > X_{opt}$?

1.2 Puzzle test-case

Consider the following task:

- Let a puzzle of square shape, with area $5 * 5$, be constructed out of 5 pieces of area 5 each with different given shapes.
- Let the final assembly shape S of this puzzle be know.
- Let the set of assembly plans P leading to the final shape S be known.
- Let the puzzle pieces assemble by bi-directional connections. One connection is enough for two pieces to be attached. These connection and their positions on the different pieces are known.
- Pieces can be assembled and disassembled.
- Consider an arena of sufficiently large size so that small scale interactions dynamics can be ignored.
- Fill this arena with N initial pieces of each shape.
- Consider M robots, able to pick up pieces and to make them assemble and disassemble.
- Allow a recognition by the robots and by the pieces of the shapes and connection points when an encounter occur.
- **Then:**
  How can you manipulate those initial pieces so that after a time T_f, the number of assembled puzzles X_S is maximized?

Consider two approaches for the robots behaviors:

1. Stochastic interactions.
   - The robots move randomly around the arena while carrying pieces.
   - They can not communicate outside of collision radius.
   - They know nothing or very little about the final assembly shape S and the assembly plans P.
   - Assembly and disassembly of pieces is random, according to specific probabilities depending on the pieces. These probabilities can be influenced by the knowledge of the final assembly shape S and assembly plans P if available.
2. Deterministic control-oriented.
   - The robots move according to specific movement patterns.
   - They can communicate outside of collision radius, in a local range R.
   - They know completely about the assembly plans P and the final assembly shape S.
   - They assemble and disassemble pieces according to their local knowledge of the environment and their internal knowledge.

1.2.1 Goal of test-case

Compare the behavior of the two controllers with respect to the final number X_S of assembled puzzles. Assert under which conditions the two different approaches are more interesting.

Classical directions for the comparison can be:

- Level of error in the system. Typical errors: bad assertion of pieces shapes and type, bad communication between errors, bad assembly of pieces, unknown initial conditions.
- Complexity level of the robots and pieces. Typical capabilities: global positioning, computing power, communication range.

1.2.2 The assembly line problem

- If we can control everything in our system, i.e. the level of error is almost zero, then why use stochasticity? More precisely, why disassemble things and not use the perfect assembly plan?
- If we are at a high enough level of complexity, then classical deterministic methods which act optimally are obviously better.
- Situations where this is not true anymore:
  1. There is intrinsic stochasticity in the process, or we cannot control it completely. Examples: self-assembly at small-scale, which stochastic dynamics.
  2. The agents make errors or the sensors are very poor. Then either you build a very robust controller or you try to correct those errors.
  3. The initial condition and the final product is not known a-priori.

Then in these situations, disassembly could be needed, and direct deterministic methods are less straightforward.

This is why a comparison according to specific environment conditions and available characteristics of the agents is needed.

1.2.3 Reformulation in the Complex System Modulation problem

Intrinsic system Problem here: we need an intrinsic system that is working on its own. So using dead-still pieces is out of question, they need to be able to move and bond randomly intrinsically.

Solution: The intrinsic system consists of the pieces and the robots with the "Stochastic interaction" behavior, with minimal design of this behavior.

Then the system will intrinsically produce some final shape X_S^i.

Augmented system The problem now is how to modify the behavior of the robots to obtain a new number of final shapes X_S^a, with $X_S^a > X_S^i$.

This could be done either by introducing new robots having designed behaviors (enforcing the partition between the two systems components), or by altering the behavior of the intrinsic robots (allowing different levels of design, but breaking the distinction between the two systems).

Typical new robots behaviors will be inspired by the Deterministic control-oriented behavior of the puzzle test-case.

2 Methodology and tools

2.1 Robotic simulation

Using Webots, construct the puzzle test-case for a given assembly shape S.

- Connections are represented by magnetic bonds. Constraints on distance and angle ranges for connections, as well as allowable shear and tearing forces can be defined.
- Radio communication is available in Webots.

Construct the two behaviors and compare them following some metric and proposed comparison parameters.

2.2 Modeling

- Use chemical reactions to represent the assembly plan.

  Rates of reactions can be obtained either:

  - As functions of geometric probabilities. For example, for two given pieces, define a probability of assembly depending on respective approaching angles and connections constraints.
  - Using Webots. Let the system run for some time while ensuring well-mixed properties. Measure the rates of reactions, that directly encompass the geometric characteristics.

- Simulate this model by Stochastic Simulation, and Hybrid Modeling. Compare the results.
- Use the model to determine ways of modifying the augmented system for optimal yield X_S^a.

3 Examples of Complex System Modulation instances

3.1 Nanoscale self-assembly

The intrinsic system consists of the possible interactions and bonds. The augmented system can be abstracted as any modification applied to the system, that modify the intrinsic behavior.

For example, changing the pH of the solution so as to activate different sticking surfaces is an action of the augmented system. Mixing the solution in a specific way, to improve aggregation in a specific area, is another possible action. The goal is then to produce such actions so that the new yield X_S^a is optimal.

3.2 LEURRE project

LEURRE is a project on building and controlling mixed societies composed of animals and artificial agents [1][2]. They built a small robot capable of infiltrating a cockroach group. The cockroach group is put in a arena with several shelters of specific luminosity. Cockroaches decides under which shelter to go according to the luminosity and the number of cockroaches under it. This is a self-organized decision process. The robot were able to infiltrate this group and to direct the global decision of the group. With infiltrated robots, they were able to force cockroaches to go under a light shelter, a configuration which was never attained with the cockroaches group only.

Intrinsic system: the cockroach group. The metric is the probability of the different shelters as final decision.

Augmented system: the cockroaches and the robots. The robots choose a different shelter, this action in turn modify the final probability of the shelters.

3.3 Enzymes

Intrinsic system: The original chemical reaction, with specific activation energy and rates.

Augmented system: The catalyzed chemical reaction with the introduction of the enzyme. The enzyme performs an action (binding with change of conformation) that helps the chemical reaction.

3.4 RNA translation into proteins

Intrinsic system: Ribosomes assemble AA according to the RNA code. The obtained first structure protein then folds itself into a specific conformation.

Augmented system: Chaperone protein helps the folding of the protein, possibly modifying the obtained conformation or allowing the initial one under different environment conditions (heat-shock response).

[1] LEURRE homepage. http://leurre.ulb.ac.be
[2] Halloy et al. "Social Integration of Robots into Groups of Cockroaches to Control Self-Organized Choices" Science (2007).