Benefits and Issues Raised From Use of Self Organisation in Practical Applications

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Introduction

As observed in nature, strictly simple actions can interact in such a way that complex behaviour is simulated. Look at, for example, the swarm of fireflies - each firefly following a very simple set of rules dictating when it blinks, creating a swarm of beautiful, patterned lights - or the ant colony, where each ant simply explores blindly and follows the instructions given by pheromones, resulting in extremely complex behaviour surrounding the collection of food and ant-based construction to reach new areas. These are examples of emergent Self Organisation, which can be replicated in software to great effect - for example, the Game of Life, where simple rules create highly complex interactions.

This analysis shall investigate the benefits and issues raised from the use of Self Organisation techniques in practical applications, justified conceptually and practically, from existing literature, and describe the literature searching strategy used.

Literature Searching Strategy

After the main talking points of the analysis had been decided, some core pieces of literature were identified. A process of reference chasing was used to build up supporting papers, and every paper found was read through to establish relevance. An annotated bibliography was then created from all relevant papers and sorted into themes. This bibliography contained all necessary information along with a summary of talking points, results, and reliability and limitations of the results.
This methodology has been fairly successful, as there is a wide variety of referenced literature, mostly established as performing well supported claims and studies, across a variety of related topics. The content provided should be reliable, and where it is possible that the source is unreliable or a study has been poorly performed, it has been noted in the text, as the claims or theories provided may still be interesting.

All literature referenced in this analysis has been peer reviewed or was presented at a conference with additional citations, and literature with no citations have been commented on in the text.

Conway's Game of Life

Much effort has been placed into the exploration of Self Organisation techniques, with some of the earliest breakthroughs opening up new areas of research. One such, very classical, area is Conway's Game of Life (GoL) - very basic rules applied to automata cells on a grid can give rise to highly complex patterns and fractals developing over time, including the development of controlled patterns such as Conway's periodic forms and translating oscillators. While not in of itself applicable to any practical problems, it is one of the first examples of Self Organisation successfully applied to computer algorithms, with the basics explored by Bays (2010).

Exploring Conway's GoL further can yield interesting, though theoretical results. Since the game can be played across any number of dimensions, and Conway identified the ability to create patterns with specific uses on the grid, it is inevitable that the game can be used to create more advanced actions yielding useful results - a computer within a computer. One of the most basic forms of useful computing is the Turing machine - which Rendell created within the GoL and published in his paper. A universal Turing machine represents a huge leap in complexity, all arising from the same basic two rules followed in Conway's GoL, initialised with complex patterns predefined on the edge of the grid, with more patterns injected at the edge of the grid. As concluded in the paper, this creation is not directly applicable to a practical problem, but it does prove that, should physical matter be 'coded' to operate as cellular automata, it would be capable of complex repetitive patterns at a useful speed, while also demonstrating that "practical use can be made of a cellular automaton by injecting patterns from the edges rather than having to initialise patterns in the bulk of the material" (Rendell 2011). Further research performed using these principles has been carried out, including in the development of a mechanical system of mobile particle swarm control by A.T et al. (2019), image scrambling with extremely high performance and image encryption abilities by Kechaidou and G. Sirakoulis (2017), and the implementation of Quantum-dot Cellular Automata with simulation-validated efficacy by Liolis, G. C. Sirakoulis, and Adamatzky (2021), among others. These works range from 2017 to 2021 in published dates, showing that the full use case of this work is both modern, and still being expanded upon, with generally positive results.

Practical Applications

Away from Conway's GoL, a number of benefits to using Self-Organisation in practical applications have since arisen. One such application, researched by Tyrrell, Auer, and Bettstetter (2006) is in the synchronisation of server nodes on a network, which can be achieved by using the natural example of firefly synchronisation, by which an independent set of nodes (fireflies) following the simple rule of slightly modifying its flashing pattern to align with all other nodes within sight or range, until over time every node is fully synchronised - with more detailed overviews available by Camazine et al. (2001) and Raghavachary (2003). By applying this logic to a set of fully meshed nodes on a network, the nodes can become time synchronised, resolving the requirement of all nodes on a server having a synchronised internal clock. As shown in the paper by Tyrell et al., the method could be used to great effect; in their case, achieving synchronicity in 15 periods with an approaching zero failure rate. However, this method does contain issues - Self-Organisation rules are not directly applicable when accounting for transmission delays and for nodes being incapable of sending and receiving signals simultaneously, as the firefly effect assumes that both are possible. Solutions for these issues are proposed in their paper by modifying the rules of Self-Organisation. A more problematic issue is that of the "deafness effect" - whereby two distinct groups of nodes arise from a non-fully meshed server, running on different clock synchronisations. In this case, Self-Organisation creates more issues than are resolved.

Another established area of the practical implementation of Self-Organisation is that of construction - whereby modular or continuous units or robots can self-assemble to perform some assigned task. Modular structuring has been in use for many years, as shown by Applegarth et al. (2005), whose well cited study has shown that non-polymer molecules can be used to bridge molecular gaps through innate self-organisational properties, which may additionally be manually prompted through impulses. Modular construction is now a widely researched area across many domains, such as the successful investigation into Self-Organisational modular network architectures by Okujeni and Egert 2019, which showed that modular Self-Organisation applied

to a network (in this case, a neuron environment) greatly increases activity generation, perpetuation and propagation, neural synchronisation function - though also increasing dysfunction. In the realm of robotics, Yu et al. 2007 set out to propose an algorithm capable of allowing modular robots to achieve a variety of environmentally-adaptive shapes, while proving that the algorithm both works and is highly responsive in performed simulations.
The area of continuous Self-Organisation is, however, newer. Heinrich et al. 2016 performed physical tests utilising 12 mobile robots designed to function as a continuous material, constructing scaffolding to support the growth of a plant in a bio-hybrid construction mechanism. The tests proved that the approach is feasible, that braids of continuous material can be created from multiple materials with embedded sensors, with no identified drawbacks - although further work in the field is required.

Self-Organisation may also be used to supplement other algorithms and processes. For example, Varughese et al. 2016 explore combining firefly synchronicity with the chemical release and swarm mechanics of slime mold cells, resulting in a swarm of self-organising robots which is capable of searching an area and finding the local maxima/minima, while responding to external forces in an attempt to save energy. This concept was explored in a mathematical simulation, proving capable of completing its objective in any case with minimal energy usage, but was not proven beyond a simple gradient environment, and it was shown that the time taken to perform this operation was excessively long, possibly taking months in a realistic environment.

Analysis

While several benefits of using Self-Organisation in practical applications have been found, there are some drawbacks which have been identified. Some research in this area simply requires more study and experiments, alongside refinement - the study into continuous construction methods and the slime mold cell combined with Self-Organisation both require additional study in a variety of environments to determine how feasible they can truly be. The study of network node synchronicity raises an issue specifically with the way Self-Organisation works - if two discrete groups can develop where there should only be one, then synchronicity will not be achievable regardless of the number of phases performed. This issue is one that can be easily transferred to any other application of Self-Organisation. Issues have also been raised in specific fields - specifically, study into the use of Self-Organisation on neural nodes raises the possibility that levels of dysfunction rise alongside function and activity. The study into marine navigation has also seen no additional development in the last 5 years from any groups, possibly indicating that there is no benefit to this particular approach - although it is mentioned that real world feasibility tests will be performed, which may have been delayed due to the ongoing pandemic.

Despite these drawbacks, the benefits are obviously large, and have resulted in a vast amount of study across many fields. The literature reviewed here is sourced from research into neural activity in biological journals, to the development of organised chemical compositions capable of molecular level construction, to a Turing machine built entirely on Self-Organisation principles, to automatic robotics. Where found, ways around the drawbacks have been implemented; as an example, the modification of the Self-Organisation ruleset for server nodes by Tyrell et al. Where there are no alternatives, clear limitations to the application of the principles have been laid out; for example, the excessively long simulation times of self-organising mold cell automata as identified by Varughese et al. has been clearly stated as requiring more research and optimisation to provide a realistic benefit. This area of research is actively ongoing, and shows no signs of slowing anytime soon - there is a bright future for the applications of Self-Organisation.

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