Morphogenic Systems Engineering for Self-Configuring Networks

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***Abstract*—We propose Morphogenic Systems Engineering as an approach for enabling military communications systems to be self-configuring. This long range research objective seeks to determine how communications systems can bootstrap themselves into existence from primitive configurations with minimal administrator intervention or supervision. The goal is to enable tactical communications networks to be fully autonomous in such ways that enhance rather than detract from force capability, operational tempo, or commander's intent.**

I. Introduction

Modern communication networks are complex systems and notoriously difficult to administer. Military tactical networks in the battlespace are even more so because of the mobile, high-tempo and hostile environment that they operate in. Despite the enormous efforts that have been applied to developing network management technologies, the sustainment of these systems still requires a high number of skilled professionals.

One indication of the complexity of communication systems is to count the number of classes in the industrial standards for management information models – CIM for the enterprise case [1] and SID/NGOSS for the telecommunications' industry [2]. The relatively light-weight standard (CIM) has hundreds of classes (SID has thousands) and this figure only merely represents the static complexity of the system. In use, the dynamic operation of the system would involve many times more objects. In a rather loose way, we feel that these systems have approached a level comparable to biological system complexity.

Complexity in the management of military networks presents commanders several problems:

- The need to have and retain skilled people to configure and maintain communication services.
- The configuration of tactical networks in the battlespace constrains operational tempo – the time it takes to move and re-establish communications services are on the critical path of any commander's movement plan.
- The dependency of commanders on a small number of skilled people operating complex equipment represents a risk in their plans.

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If networks were self-managing, force capability would be significantly improved. In this paper, we mean "self-managing" to be short-hand for self-configuring, self-healing, self-optimising and self-securising – the four key self-X behaviours in IBM's recent manifesto on Autonomic Computing [3].

The purpose of this paper is to propose a novel approach to the self-configuration dimension of autonomic systems management. The question on view here is as follows: *is it possible for a mature, well configured military communication system to bootstrap itself into existence from a "stem cell" configuration?* If we accept that communications systems complexity is comparable to biological systems complexity, then it makes engineering sense to look at biological mechanisms for system development. Within the biological community, such studies are titled morphogenesis or embryogenesis [4], hence we've given the name morphogenic systems engineering to approaches which look at computational methods that address this question.

II. Theory

A. Configuration Spaces

The components of communication systems require detailed configuration before these elements can function within the system. Configurations are specifications of desired operational behaviour and usually represented in the form of appropriately formatted files. In our model, these configuration files may be seen as forming a type of genome, albeit quite different from the more familiar biological form of DNA.

Maintaining the analogy, the associated run-time services that are generated when a computer (/router/switch/etc) is booted up may be seen as the corresponding phenotype of the system's configuration files. It is our hope that this genotype↔phenotype analogy may provide useful insights into better means for producing robust autonomic properties for military communication systems in the tactical network environment.

As a first step, we wish to find mechanisms for which networks can be self-creating in the sense that they can bootstrap themselves (self-configuration) into an appropriate, mature and functional mode of operation. The biological pattern for this is the single cell fertilised egg which has the potential through a process of morphogenesis to grow into an adult.

In the biological case, it is the genome of the original egg that has the configuration information that in combination with cellular chemistry that allows it to become an adult (the phenotype).

Taking a systems engineering perspective, our approach is to begin with a specification of the desired properties of the "adult" system and then search for a genome that can produce this system as the phenotype.

III. EXPERIMENT

Networks are usually configured from a static set of preinstalled files (config files). When the devices in the network boot up, they read their config file to determine what their run-time services should be and how they are to operate. In our model, the set of config files forms a type of genome. The collective set of runtime services gives rise to the network phenotype. Since genomes codify the static configuration information for a phenotype, *how possible is it to automate the evolution of configuration files for networks?*

We've constructed a simple toy problem that illustrates the features of this approach and acts as a visual metaphor. The requirement is to begin with a modified cellular automata (CA) which is 3×17 cells in size. It initially consists of a single cell – the stem CELL[1] which has a unique genome inserted into it that consists of a data structure made up of only five atomic cellular operators:

1. STOP – no more development of the CELL
2. NOP – no operation this time step
3. KILL(N) – kill the neighbour CELL at cell position N.
4. MOVE(N) – Move to the position at neighbour cell N.
5. SPAWN(N) – Create a new CELL at neighbour cell N.

At each time step, each CELL in the CA executes only one of the five operators according to an internal index each CELL maintains into the genome data structure. The experimental question is can we find a genome data structure that when inserted into the stem CELL will produce the word "HELLO" in a reasonable number of steps?

The "HELLO" word is the phenotype system function we want expressed and the genome is the genotype configuration file we are searching for.

For the genome data structure, we've adapted the cellular encoding method developed by Gruau [5], originally designed for evolving neural networks. It is a tree data type that is composed of the five cellular operators described above along with nine symbolic terminals that reference the Moore neighbourhood of a cell.

We constructed a genetic-programming (GP) searcher based on the software ECJ[2] for searching through the space of possible configurations. The breeding pipeline for this GP searcher is shown in Figure 1. The fitness measure for this problem is multi-objective consisting of two measures:

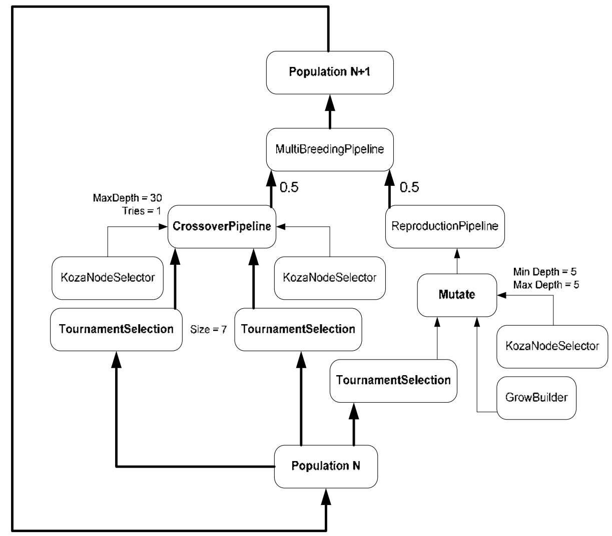

Figure 1 Breeding Pipeline for the Genetic Programming Search

1. A score based on XOR-ing the resulting space with the desired space.
2. A score based on the difference in the number of CELLs of the resulting space and the desired number of CELLs.

IV. RESULTS

With an "untuned" breeding pipeline, we were able to obtain a good result in this toy space, considering that even in this "small" problem the search space is 2^{51} possible phenotypes. The final genome used here has 1,996 nodes with a tree height of 38.

Figure 2 shows the morphogenic progression of a single stem CELL every five time steps. The first picture at time step 0 shows the placement of the original stem CELL in the CA. The last picture shows the final configuration which achieves the required system function.

Operating within our analogy, the meaning of this result is that it shows that it is possible to use evolutionary processes to find configuration files (genomes) for a desired network function (phenotype).

There are several improvements possible to the GP search but the most significant benefit would be to improve the genetic cross-over and mutation operators to select with higher probability nodes deeper in the tree rather than uniformly over the tree. The reason is that these operators when selecting shallow in the tree tend to destroy previously obtained fitness improvements. Much of the final fitness improvements are to be found in modifying towards the leaves of the tree.

V. CONCLUSION

The HELLO problem shows quite clearly how the desired global system function arises from the single stem cell. It also is a useful hypothesis generator, since quite a few questions immediately arise:

[1] There is a double meaning to the word cell which we clarify as follows. "CELL" (upper-case) means a cellular automata *machine* derived from the stem CELL. "cell" (lower-case) means a *position* in the cellular automata.

[2] http://cs.gmu.edu/~eclab/projects/ecj/

- How robust is the system function to unplanned individual CELL deaths?
- How viable is the approach for even larger search spaces?
- What advantages are conferred if we adopted more biological patterns for morphogenesis. For example, cellular differentiation, morphogenic fields, etc.

However, it maybe the insights these examples give that are most useful for systems development. In the HELLO problem, we used five primitive "CA space" operators as the foundation for the genome. For network problems, we require different operational primitives appropriate to the system functions we wish to express. The identification of these primitives are context dependent on the particular problem we are trying to address: communications middleware problems are likely to have a different set of primitives when compared to object persistence/storage/database primitives. However, we maybe able to organise these primitives in similar ways giving us a general advantage to systems development.

We see the potential opportunities to network management as follows:

1. *How far can we automate the development of network configuration files by using computational evolutionary processes?* Networks are both spatial systems and temporal systems. The spatial aspect of networks most obviously includes the physical topology of the devices in the domain, but it also can include the much more complex connections between abstract components and sub-systems in and between devices. Networks change over time for many reasons. Of course, it is highly desirable that these structures are "optimised" in some sense. The HELLO problem seeks to solve a spatial problem. In Network Management Systems, the "space" is the complex phenotypic expression of services generated by the configurations for each network device (e.g. Cisco IOS conf files, etc).
2. *Can we automate the deployment of management services morphogenically?* Can we use this approach to develop technology which facilitates the deployability of network management systems via "stem cells" which when sent to the field they rapidly "grow" in their tactical environment to become a fully functional, useful network system.

We also recognise existing system configurations are manually evolved specifications derived from years of selection pressures occasioned by experience, doctrine, training and human skill. Finding mechanisms which automate much of this effort is an important contribution to the improvement of the defence capability.

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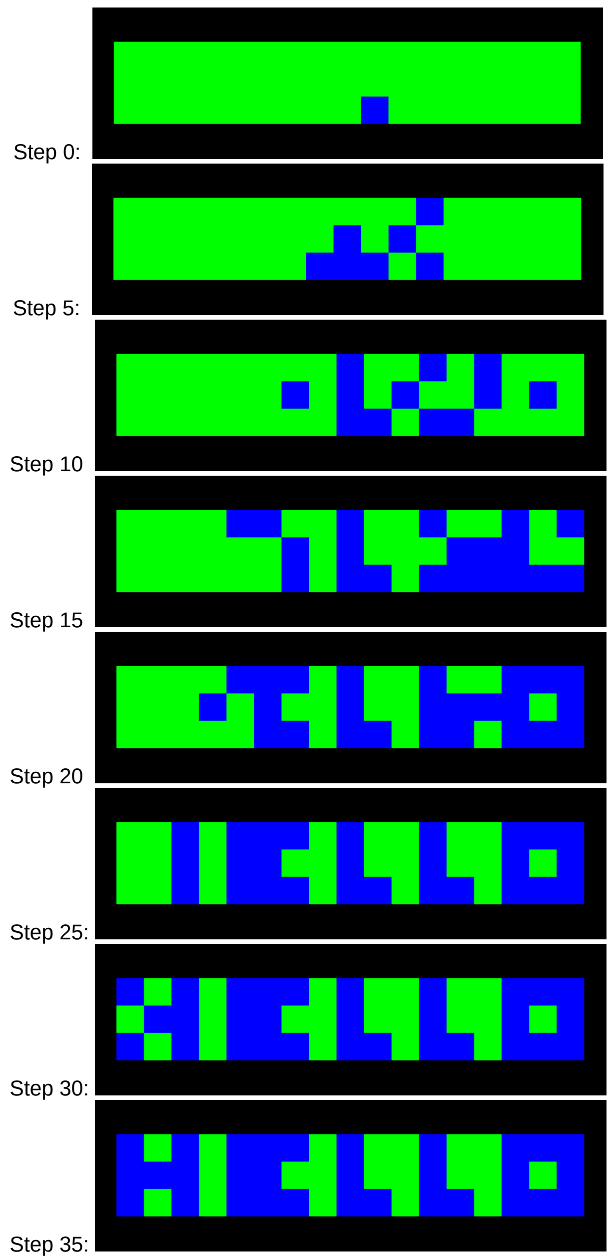

Figure 2 Morphogenesis of "HELLO" from a single stem cell