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Evolutionary strategies for ultra-large-scale autonomic systems

Michele Amoretti *

Centro Interdipartimentale SITEIA.PARMA, Università degli Studi di Parma, Italy

A R T I C L E I N F O

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A B S T R A C T

Ultra-large-scale (ULS) systems originate from the need to address social problems that are getting more and more complex, such as climatic monitoring, transportation, citizens protection and security. These factors imply a continuous increase of information systems, requiring digital communication networks allowing for communication between people, between machines, and machines and people. The aim of this paper is to present a novel approach for the design of highly adaptive ULS systems, with the focus on computer-supported evolution, adaptable structures, emergent behaviors as well as advanced monitoring and control techniques. We illustrate the Networked Autonomic Machine (NAM), a framework for the characterization of self-managing, highly reconfigurable ULS systems, and the Adaptive Evolutionary Framework (AEF), for the implementation of distributed evolutionary strategies. Finally, we show their effectiveness in the design of an ULS overlay network provided with evolutionary strategies for facing denial-of-service attacks.

1. Introduction

An *ultra-large-scale* (*ULS*) system is a system of unprecedented scale in some of the following dimensions: lines of code, amount of data (stored, accessed, manipulated, and refined), number of connections and interdependencies, number of hardware elements, number of computational elements, number of system purposes and user perception of these purposes, number of routine processes, interactions, and emergent behaviors, number of (overlapping) policy domains and enforceable mechanisms, number of people involved in some way [42]. Examples of ULS systems are the Internet [11], super-national power grid management systems, healthcare infrastructures, e-markets, global ambient intelligence systems.

An ULS system is complex, in the sense that it is composed of several interconnected parts that as a whole exhibit one or more properties (*i.e.* emergent behavior) which are not easily inferred from the properties of the individual parts [45]. Thus, breakthrough research is necessary to face fundamental challenges in the design and evolution, orchestration and control, and monitoring and assessment of ULS systems. Specific challenges in ULS system design and implementation include legal issues, enforcement mechanisms and processes, definition of infrastructural services, rules and regulations, handling of change, integration, user-controlled evolution, computer-supported evolution, adaptable structure and emergent quality.

In this work we focus on the design and analysis of highly adaptive ULS systems, characterized by mutable structure, emergent behaviors as well as advanced monitoring and control mechanisms. The overall vision is that of ULS networked systems whose software entities are able to self-design, self-configure, self-monitor, self-deploy, self-heal (self-* properties, from now on) – in other words, ULS autonomic systems which are able to operate in a totally unsupervised manner. One key aspect is the ability of foreseen self-refactoring systems to deploy and un-deploy functional modules, according to context

* Tel.: +39 0521906147.
E-mail address: michele.amoretti@unipr.it

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and reasoning, in order to maintain the desired quality of service in a varying and challenging environment. The latter may include users, whose interaction will affect the adaptation process of ULS autonomic systems.

Three important objectives need to be pursued to fulfill this vision. The first one is the *lack of centralized goals and control*. Decentralization increases the robustness of the services at a microscale, and encourages new applications at a macroscale. The second objective is *meaningful adaptation*. The envisioned ULS autonomic systems are able to adapt correctly to given stimuli, maintain key behaviors and avoid deleterious ones – using evolutionary computation. Designers have to take into account emergent behaviors, for which it may happen that local optimizations lead to global performance improvements, but also to global unexpected failures. The third objective is *cooperation in the face of competition*, for which free-riding and selfish behaviors must be detected and rendered harmless. These challenges cannot be independently dealt with. On the contrary, they need to be woven into a coherent solution to be evaluated with respect to well-established performance metrics for distributed systems.

To cope with these objectives since the design phase, it is necessary to define and adopt innovative modeling tools that support the design of ULS autonomic systems. The novel approach we propose to model ULS autonomic systems and design their distributed self-management mechanisms is based on the combination of two architectural models, namely the *Networked Autonomic Machine* (*NAM*) and the *Adaptive Evolutionary Framework* (*AEF*). Both NAM and AEF have been introduced in previous research papers [2,3], but this is the first work in which we put them together, being highly motivated by the challenging issues that ULS systems present.

With NAM, it is possible to design autonomic ULS systems that detect, diagnose and repair failures and adapt their behavior to changes in the environment. By means of distributed context-awareness mechanisms, NAMs are enabled to sense network conditions and the quality of provided services, and perform corrective actions. Context-based information sharing can be realized through dissemination of specific data among different nodes or through cross-module and cross-layer messages inside the same node. For example, a QoS entity responsible to allocate network resources may exchange context-aware information with other nodes, to identify changes in network conditions. Moreover, context-based distributed self-monitoring is finalized to the automatic refactoring of software entities that compose the ULS system. Importantly, It is possible to move from a NAM high-level model to a discrete event representation of its dynamics, which is very important for simulation purposes.

According to the AEF, the internal structure and/or configuration of a NAM may change by means of an adaptive plan, in response to modifications of the environment. The adaptive plan is a general evolutionary strategy, not a "functional plan". Indeed, NAMs are truly autonomic systems whose self-* properties are not necessarily "designed": most of them emerge at runtime. Like biological systems, the emergence of a function – the ability of a system to perform a task – can be guided by its environment, without imposing a rigid blueprint [45]. In our previous works [2,3] we focused on the case of nodes having fixed structures, each one consisting of the same number of elements, and applied the AEF to dynamically reconfigure nodes. Here, by applying for the first time the AEF to the NAM framework, we investigate the more general case of evolving structures.

The rest of the paper is organized as follows. Section 2 presents the state of the art in the design of ULS autonomic systems. Section 3 introduces the case study of an ULS overlay network, provided with evolutionary strategies to face Denial-of-Service (DoS) attacks which attempt to fragment the topology. Section 4 illustrates the NAM framework for high-level modeling of ULS autonomic systems, also discussing the problem of the system dynamics characterization with computational modeling tools. Section 5 recalls the principles of the AEF, and sets it in the context of ULS autonomic systems. Section 6 illustrates how to use the proposed modeling approach for designing and evaluating the ULS overlay network of the case study. Finally, Section 7 concludes the paper, with a discussion on achieved results, and an outline of future work.

2. Related work

The SEI study [42] brings together experts in software and other fields to examine the consequences of rapidly increasing scale in software-reliant systems. The report defines a broad, multi-disciplinary research agenda for the development of future ULS systems.

The modeling, analysis and development of ULS systems comprises a number of technical challenges. Many of them can be classified as belonging to one of the following areas: massive numbers of nodes per system, open and non-deterministic environments, and adaptation [28]. The development of multi-core processors with tens to thousands of cores integrated on a single chip implies that even single-chip systems have to be treated as consisting of large numbers of individual nodes. Furthermore, new manufacturing methods – such as nanotechnology or synthetic biology – will give rise to new types of ensembles, many of them with potentially millions of computational nodes. Such a trend will be further boosted by the introduction of the IPv6 protocol suite [6], which uses 128-bit long IP addresses, thus allowing approximately 3.4×1038 nodes with unique identifier in the Internet, *i.e.* more than 7.9×1028 times as many as IPv4. Last but not least, future systems will often have to operate under conditions that differ significantly from the ones for which they were designed. They should not only be able to adapt to changes in their network environment, they should also be able to work reliably in the face of changes to their execution platform. As adaptation in ULS systems is the main topic of this article, the remainder of this section focuses on it.

The research agenda proposed by the SEI study includes computer-supported evolution, adaptable structure and emergent qualities of ULS systems. All these aspects can be placed under the umbrella of *Autonomic Computing*, which proposes to provide