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Developing pervasive multi-agent systems with nature-inspired coordination

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ABSTRACT

Pervasive computing systems can be modelled effectively as populations of interacting autonomous components. The key challenge to realizing such models is in getting separately-specified and -developed sub-systems to discover and interoperate with each other in an open and extensible way, supported by appropriate middleware services. In this paper, we argue that nature-inspired coordination models offer a promising way of addressing this challenge. We first frame the various dimensions along which nature-inspired coordination models can be defined, and survey the most relevant proposals in the area. We describe the nature-inspired coordination model developed within the SAPERE project as a synthesis of existing approaches, and show how it can effectively support the multifold requirements of modern and emerging pervasive services. We conclude by identifying what we think are the open research challenges in this area, and identify some research directions that we believe are promising.

1. Introduction

The multitude of pervasive computing devices that populate our everyday environments – embedded sensors and actuators, smart phones, personal see-through displays, interactive public displays, and smart objects, to mention only a few – are leading to the emergence of a dense, decentralized infrastructure, which can provide a wealth of services in an un-intrusive manner [1–3]. This infrastructure will necessarily be open to contributions from a range of vendors and other users, and will be used to deliver and access services for interacting with the surrounding physical world and with the social activities occurring within it [4–7].

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To support such a vision, a great deal of research activity in pervasive computing has been devoted to addressing the problems associated with the development of effective pervasive service ecosystems. The research issues include supporting context-aware composition of service components [8,9]; enforcing self-adaptability and self-organization in services [10]; and ensuring that service frameworks can be flexible enough to tolerate service diversity and evolution [11]. While a general-purpose approach to support the development of such systems is still missing [12], the key requirements that such an approach should support have been extensively analysed [11]. They can be re-formulated as follows:

Situatedness — Pervasive services are typically time- and space-dependent, and feature physically- or socially-situated activities. Components of pervasive systems should be able to interact with the surrounding physical and social world by adapting their behaviour accordingly.

Autonomy and self-adaptivity — While individual components should be autonomous in the face of the inherent dynamics of their operational environment [13], pervasive systems should also feature *system-level autonomy* to deal globally with the unpredictability of the environment, providing properties such as self-adaptation, self-management, and self-organization [14].

Prosumption and diversity — Infrastructures for pervasive systems must promote open models of component integration, to be able to take advantage of the injection of new services and components [15]. This is particularly true in the context of *socio-technical systems* [16], where human users and software agents act as *prosumers* – both consumers and producers – of devices, data, and services.

Eternity — As well as short-term adaptation, a pervasive systems infrastructure should allow for the long-term evolution of organizations, components, and patterns of usage, in order to accommodate technological advances as well as the mutable needs of users without requiring extensive re-engineering effort [17]. In fact, pervasive systems are better conceived as *eternal* systems, engineered for continuous, unlimited service, upgrading, and maintenance over time.

The way to identify suitable approaches for the engineering and development of complex pervasive service systems is to state the problem in terms of *engineering the coordinated activities of a multitude of decentralized autonomous components*: that is, as a dynamic coordination problem for multi-agent systems [15] (MAS from now on). The different hardware and software components that provide pervasive services are decentralized and embedded in a dynamic environment, that is typically controlled by multiple stakeholders (municipalities, industries, private users) and is intrinsically dynamic due to mobility and intermittent availability. Accordingly, their behaviour cannot be subjected to a predictable flow of control, and they should be rather modelled in terms of components exhibiting observable autonomous behaviour, that is as agents [15,18]. The same considerations clearly apply to those components that by their very nature have autonomous internal decision-making, such as mobile robots, self-driving cars, and humans. Consequently, composite services cannot be engineered on the basis of static patterns of orchestrated activities such as happens in the business process domain. Rather, they must base their activities on a suitable *coordination model* [19] that captures the appropriate dynamic composition patterns, adaptable to the context and situations the system finds itself in, and offering fully decentralized orchestration, within an associated *coordination infrastructure*. *Coordination* has been defined as the science of managing the space of interaction [20]. Coordination models and their associated middleware infrastructures provide the basic abstractions and technologies for dealing with the engineering of complex component interactions, especially in large-scale, open MASs [21,22] such as are found in pervasive systems.

Among the variety of possible approaches to coordination in modern pervasive systems [12,19,23,24], a very promising one is to take inspiration from nature. Indeed – given the very different kinds of natural systems that effectively coordinate the activities of their components in a context-aware, self-adaptable, and flexible way [11] – one could argue that a coordination model that uses natural metaphors to express distributed algorithms and coordination patterns provides a "natural" way to think about distributed computation.

In recent years a variety of nature-inspired algorithmic solutions and patterns have been applied to deal with specific aspects of self-adaptability and openness in specific distributed and pervasive contexts [14,25,26]. Yet a comprehensive framework defining a general-purpose coordination approach to pervasive systems is still missing.

Against this background, this paper presents the following contributions and insights. In Section 2 we introduce the key concepts underlying coordination models and infrastructures, and analyse the suitability of nature-inspired coordination models for the engineering of complex pervasive multi-agent ecosystems. We survey the most relevant proposals in the area of nature-inspired coordination models, and the associated proposals for middleware infrastructures in Section 3. Section 4 presents the SAPERE approach [27], that synthesizes and generalizes existing approaches and was specifically conceived to engineer and support the execution of complex pervasive MASs. As discussed in Section 5, SAPERE makes it possible to easily program a variety of nature-inspired self-organization patterns. We identify some remaining open challenges in Section 6, and identify some promising research directions, before offering some overall conclusions in Section 7.

2. Towards nature-inspired coordination

In this section we introduce the key concepts behind coordination models and infrastructures, focusing in particular on tuple-based coordination models, and motivate the suitability of nature-inspired coordination models for pervasive MASs.