Nature-Inspired Coordination for Complex Distributed Systems

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Abstract. Originating from closed parallel systems, coordination models and technologies gained in expressive power so to deal with complex distributed systems. In particular, nature-inspired models of coordination emerged in the last decade as the most effective approaches to tackle the complexity of pervasive, intelligent, and self-* systems. In this paper we survey the most relevant nature-inspired coordination models, discuss the main open issues, and explore the trends for their future development.

1 Introduction

Coordination models essentially address the issue of how to harness the complexity of the interaction space in the design of distributed systems [26]. Even though originating in the context of closed, parallel systems [6], coordination models soon gained relevance and power in those scenarios where complexity is a key factor—such as intelligent, knowledge-intensive, pervasive, self-organising systems [3].

Coordination, indeed, is not a matter of computational systems only. In fact, it concerns complex systems of any sort: roughly speaking, it is how complex system get together so as to work [17]. Many natural systems are prominent examples of complex systems exhibiting models and patterns of coordination that enforce desirable properties for computational systems such as fault-tolerance, adaptiveness, and self-organisation. Accordingly, a whole class of coordination models is inspired by the extraction of abstractions, patterns, and mechanisms out of natural systems: *nature-inspired* coordination models come from the idea that working complex systems exist in the real world, which we can observe so as to understand their basic principles and mechanisms, to abstract them, and to bring them within our computational systems [28]. In particular, understanding the principles and

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mechanisms of coordination within complex natural systems is seemingly an effective approach for the definition of coordination models and computational technologies for complex distributed systems.

2 Nature-Inspired Coordination: Early Examples

Historically, nature-inspired models of coordination are grounded in studies on the behaviour of social insects, like ants or termites. In [8], Grassé noted that in termite societies *"The coordination of tasks and the regulation of constructions are not directly dependent from the workers, but from constructions themselves."*, and introduced the notion of *stigmergy* as the fundamental coordination mechanism. For instance, in ant colonies, pheromones act as environment markers for specific social activities, and drive both the individual and the social behaviour of ants.

Nowadays, stigmergy generally refers to a set of nature-inspired coordination mechanisms mediated by the *environment*: digital pheromones [19] and other *signs* made and sensed in a shared environment [18] can be exploited for the engineering of adaptive and self-organising computational systems. By interpreting tuples as signs, and tuple spaces as environment abstractions, tuple-based coordination models [21] – derived from the original LINDA model [6] – can be used to implement stigmergic coordination within complex distributed systems [9, 20].

More or less contemporary with LINDA is the *chemistry-inspired coordination* model Gamma [1]: as for the CHAM (chemical abstract machine) model [2], coordination in Gamma is conceived as the evolution of a space governed by chemical-like rules, globally working as a rewriting system.

On the other hand, *field-based coordination* models like TOTA [9] are inspired by the way masses and particles move and self-organise according to gravitational/electromagnetic fields [10]. There, computational force fields in the form of distributed tuples, generated either by the active components or by the pervasive coordination infrastructure, propagate across the environment, and drive the actions and motion of the component themselves.

Some of the basic issues of complex system coordination straightforwardly emerge from the above-mentioned models. First, the role of the *environment* is essential in nature-inspired coordination. Components of a distributed system are not limited to direct interaction, but they can communicate and coordinate *indirectly* through the environment. Also, the environment is *active*: it exhibits an autonomous dynamics (as in the case of chemical-like mechanisms) and affects component coordination (as in the case of pheromone-like mechanisms). Finally, the environment has a *structure* (as in the case of field-based models): interaction in complex distributed systems can then be enriched with some notion of *locality*, and components of any sort can *move* through a *topology*.

3 Nature-Inspired Coordination: Issues

Capturing *some* of the principles and mechanisms of natural systems does not ensure to capture their essence. For instance, chemical coordination models such as Gamma and CHAM exploit the raw schema of computation as chemical reaction, but are not expressive enough to fully reproduce any non-trivial chemical system. In fact, even the simplest model for real chemical reactions requires a notion of *reaction rate* (roughly speaking, a measure of how fast a reaction takes place): since neither Gamma nor CHAM provide for such a notion, they are not endowed with the expressive power required to build computational systems fully matching the behaviour of real chemical systems.

Studies on the notion of *self-organising coordination* [24] point out some general issues of nature-inspired coordination of complex systems—in particular when compared with "classical" coordination models for distributed systems. In fact, most of the traditional coordination models feature abstractions enacting coordination laws that are typically reactive, (essentially) deterministic, and global as well. In complex systems featuring self-* properties, instead, coordination patterns typically appear at the global level by emergence, from probabilistic, time-dependent coordination laws based on local criteria.

In particular, many coordination models either implicitly or explicitly recognise that full expressiveness requires addressing the issues of *time dependency* and *stochasticity*. Among the first attempts, STOKLAIM [4] – a stochastic extension of the LINDA-derived KLAIM model for mobile coordination [3] – adds distribution rates to coordination primitives, thus making it possible the modelling of non-deterministic real-life phenomena such as failure rates and inter-arrival times.

In its turn, SwarmLinda aims at enhancing LINDA implementation with swarm intelligence [22] in order to achieve many natural-system features such as scalability, adaptiveness, and fault-tolerance. This is obtained by modelling tuple templates as ants, and enhancing them with a probabilistic behaviour when looking for matching tuples in a distributed setting.

Time dependency is generally addressed by the time-aware extension of ReSpecT [14]. There, the ReSpecT language for programming logic tuple centres [2] is extended in order to catch with time, and to support the definition and enforcement of *timed coordination policies*. ReSpecT programmed tuple centres can then work as time-dependent abstractions for the coordination of distributed processes, once deployed upon the TuCSoN coordination infrastructure [15].

In the overall, however, the above-mentioned models for the coordination of complex distributed system fail to provide a comprehensive and exhaustive approach that could capture all the essential features of nature-inspired coordination. Instead, this is precisely the main target of many novel research lines, which stretch existing coordination modes (typically, tuple-based ones) to make them reach their full potential, trying to achieve the expressive power required to model and build distributed systems with a complexity comparable to natural systems.

4 Nature-Inspired Coordination: Trends

The most relevant trend in today models for the coordination of complex distributed system is aimed at expressing the *full dynamics* of complex natural systems. Along this line, *chemical tuple spaces* [23] represent a successful attempt to exploit the chemical metaphor at its full extent. There, data, devices, and software agents are represented in terms of tuples, and system behaviour is expressed by means of chemical-like laws – enacting interaction patterns such as composition, aggregation, competition, contextualisation, diffusion, and decay – which are actually time-dependent and stochastic. Chemical laws, in fact, are implemented based on the Gillespie's algorithm [1] using *uniform coordination primitives* – that is, LINDA-like coordination primitives returning tuples matching a template with a uniform distribution [5] – in order to capture the full-fledged dynamics of real chemical systems within the coordination abstractions.

Blending metaphors from different sources represents another fundamental trend. For instance, the SAPERE coordination model for pervasive service ecosystems [27] exploits the chemical metaphor for driving the evolution of coordination abstractions, biochemical abstractions for topology and diffusion, and the notion of ecosystem altogether in order to model the overall system structure and dynamics. There, all the components (data, devices, agents) are uniformly represented through special tuples called LSA (Live Semantic Annotations) which can chemically bond to each other, live within sorts of biochemical compartments (LSA-spaces), and evolve based on natural laws of the ecosystem, called eco-laws [25].

Finally, integrating nature-inspired with knowledge-oriented coordination is the last fundamental trend. Both chemical tuple spaces and SAPERE abstractions relay on the semantic interpretation of coordination items—in the same way as *semantic tuple centres* [12]. On the other hand, a nature-inspired coordination model focussing on knowledge management is MoK (Molecules of Knowledge) [11]. There, knowledge sources produce atoms of knowledge in biochemical compartments, which then aggregate in molecules and diffuse according to biochemical reactions. In MoK, the full power of the biochemical metaphor is exploited in order to achieve knowledge self-organisation within knowledge-intensive environments.

5 Conclusion

Starting from early chemical and stigmergic approaches, nature-inspired models of coordination deeply evolved aimed at becoming the core of the engineering of complex distributed systems, such as pervasive, knowledge-intensive, intelligent, and self-* systems. In this paper we shorty survey their early history, devise their main issues, and point out the most promising trends—namely, full metaphor adoption, heterogeneous metaphor blending, and knowledge-oriented integration.

In the overall, nature-inspired models of coordination already have a long history behind them, and a huge potential for development still to be explored.

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