State-of-the-Art and Trends in Nature-inspired Coordination Models

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***Abstract*—Mostly stemming from closed parallel systems, coordination models and technologies gained in scope and expressive power so as to deal with complex distributed systems. In particular, in the last decade nature-inspired coordination (NIC) models emerged as the most effective approaches to tackle the complexity of pervasive, intelligent, and self-* systems. In this review paper we discuss their evolution, by analysing the main motivations behind the research effort on NIC, the foremost features of the most successful models, and the key issues and challenges they bring along.**

***Index Terms*—Nature-inspired coordination, Coordination models**

I. Introduction: Why NIC Matters

An essential source of complexity for computational systems is *interaction* [1]. According to the early intuition of Wegner [2], in fact (emphasis added):

> "Interaction is a *more powerful paradigm* than rule-based algorithms for computer-based solving, overtiring the prevailing view that all computing is expressible as algorithms."

Coordination, then, is [3]

> "the *glue* that binds separate activities into an ensemble."

or, more operationally, a *coordination model* is [4]

> "a framework in which the interaction of active and independent entities called agents can be expressed."

Tuple-based coordination, in particular, proved over the years to be the most expressive approach to coordination, mostly thanks to some peculiar traits emphasised by Gelernter in his seminal work on the LINDA model [5]: *generative communication*, that is, the fact that information items (tuples) live independently of their producer; *associative access*, which means that information can be accessed by looking at their content, with no need to know their name or location; *suspensive semantics*, enabling synchronisation among conflicting activities by suspending and resuming operations based upon availability of data. Altogether, the above features lead to a concise and effective model for space, time, and reference *uncoupled* coordination in distributed systems of any sort.

Recognising interaction as an essential *dimension of computation* [2] impacts on the engineering of computational systems at many different levels:

- the need for brand new **programming languages** specifically devoted to program the *interaction space* arises [3]
- interaction is recognised as an independent design dimension in **software engineering** [6], with its own best practices and recurrent solutions—in the form of *coordination patterns* [7]
- interaction quickly becomes a new source of **artificial intelligence** [8]—for instance, of *social intelligence* [9]

Then, researchers observed that *natural systems* exhibit many features – such as distribution, openness, situatedness, robustness, adaptiveness – which are highly desirable for computational systems, too, and began to analyse them to understand their basic mechanisms. *Nature-inspired computing* soon became a hot research topic offering plenty of solutions to complex problems—see [10] for a short summary. In particular, the prominent role of interaction in the complexity of natural systems – as in the case, e.g., of *stigmergy* [11] – made *nature-inspired coordination* (NIC henceforth) a noteworthy subject of research for the last decades.

In the following sections, we first review some of the main proposals in the field from an historical perspective, discussing how NIC evolved from early models to future generation ones (Section II), then we look forward to the most recent research trends in the field, highlighting the challenges yet to be faced (Section III).

II. Evolution of NIC Models

Many different models have been proposed over time, drawing inspiration from disparate natural system depending on the desirable features to be extracted—i.e. chemistry, biology, ecosystems, physics, etc. In this section we review the most successful ones, highlighting their distinguishing features, and discussing the main issues involved in their engineering and deployment.

A. Early

The first NIC models to gain traction were *stigmergy-based* and *chemical-like*: the former explicitly aimed at coordinating an ensemble of autonomous agents, the latter originally aimed at providing an alternative model of computation, but later exploited and extended towards coordination needs.

1) Stigmergy: Most of NIC models are grounded in studies on the behaviour of social insects, like ants or termites. In fact, it was the zoologist Pierre-Paul Grassè to introduce the very notion of *stigmergy* as the fundamental coordination mechanism in termite societies [11]. There, termites release special chemical markers in the environment – called *pheromones* – to influence other termites activities: in this case, nest building.

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In this way, a form of indirect communication – called *environment-mediated* communication – favours coordination amongst distributed agents, and the coordination process itself is influenced by the structural properties of the environment: in fact, pheromones evaporates, is usually perceived locally – within some range –, and accumulates—insects perceive their "amount".

Stigmergy-based coordination has been then proficiently brought to the computational world by approaches such as *digital phermonones* [12], fostering digital "signs" (or markers) deposited in a shared environment [13] able to steer interacting agents activities—i.e. in the field of unmanned veichles.

2) Chemistry: Another early source of inspiration for NIC has been *chemistry*. The intuition here is that complex physical phenomena are driven by (relatively) simple chemical reactions, which to some extent "coordinate" the behaviours of a huge amount of components (molecules, for instance), as well as the global system (a cell, an organism) evolution.

Gamma [14] and CHAM (CHemical Abstract Machine) [15] are the earliest and most successful examples of this kind of NIC: the former is a novel approach to computation fostering *multiset rewriting* as the core processing mechanism, later specifically tailored to coordination in shared spaces, whereas the latter is an abstract computational model interpreting processes execution as a *chemical process*.

The two aforementioned models provide the basis for many later models and approaches to chemistry-inspired NIC, among which *biochemical tuple spaces* (Subsection II-B1) and MoK (Subsection III-B)

B. Modern

Based upon the early approaches just described, many models have been conceived as an extension, refinement, or combination of them, either as general-purpose coordination approaches or tailored to specific application domains. Also, thanks to the early success of the models described above, research in NIC further expanded to more heterogeneous sources of inspiration, there including, for instance, physics and swarming.

1) Biochemistry: Chemical tuple spaces [16] developed the Gamma and CHAM models to their full potential: data, devices, and software agents are represented in terms of chemical reactants, and system behaviour is expressed by means of chemical-like coordination rules; these rules are time-dependent and stochastic *exactly* as they are in natural chemistry. *Biochemical tuple spaces* (BST) [17] add a notion of *topology* and *distribution* to the picture, through the notion of compartments and diffusion.

The effectiveness and appeal of (bio)chemical coordination models is witnessed, for instance, by the SAPERE EU project [18], fostering a fully decentralised approach to coordination of pervasive systems deeply rooted in (and also hugely extending) the BTS model.

2) Field-based: Field-based coordination models like Co-fields [19] are inspired by the way masses and particles move and self-organise according to gravitational/electromagnetic fields. There, computational force fields propagate across the (computational) environment, and drive the actions and motion of the interacting agents.

TOTA [20], for instance, is a coordination middleware based on the co-fields model where interacting agents share tuples embedding a rules to autonomously spread in a network so as to create *computational gradients* used to coordinate agent actions and steer their activities towards a collective goal.

3) Swarms: Swarm intelligence [21] has a long tradition of models and algorithms drawing inspiration from *ecological systems* – most notably ant colonies, birds flocks, schools of fishes – to devise out efficient and fully decentralised cooperation/coordination mechanisms—mostly exploited in *swarm robotics* [22]. Along this line, SwarmLinda [23] proposes a tuple-based model for *swarming-based* coordination, where tuples and tuple templates are interpreted as food and artificial ants, respectively, and where the tuple-matching mechanism and tuples distribution in the network of tuple spaces are inspired to food harvesting and brood sorting, respectively.

Many applications in the general area of swarm robotics [24] exploit similar ideas—such as, for instance, cooperative transport [25].

C. Next Generation?

The more NIC becomes mature – and, with it, NIC models gets refined and stable – the more is likely that the original metaphor becomes less visible and somewhat mixed in with other approaches, either nature inspired or not, in order to optimise effectiveness and improve flexibility.

A notable and recent example is *aggregate computing* [26], which promotes a paradigm shift from programming devices to programming ensembles of devices, in a sort of spatio-temporal continuum. The aim is to simplify the design, creation, and maintenance of large-scale software systems [27] such as IoT, cyber-physical systems, pervasive computing, robotic swarms.

The roots of the model are in computational fields [19], chemical coordination [16], as well as *spatial computing* [28]—yet, all those sources of inspiration are blended together to create a very unique and novel programming paradigm.

D. Issues

Despite their heterogeneity, both as regards their source of inspiration and their actual design and implementation, all the models described above share a few critical issues to be dealt with so as to successfully and faithfully realise them:

- **environment** is essential in nature-inspired coordination
  - it works as a *mediator* for agent interaction, through which agents can communicate and coordinate indirectly
  - it is *active*, featuring autonomous dynamics, and affecting agent coordination
  - it has a *structure*, requiring a notion of *locality*, and allowing agents of any sort to move in a topology

  For the reasons above, careful *environment engineering* [29] based on well-defined meta-models – such as the

A&A meta-model [30] – inevitably becomes a fundamental step in the software engineering process of a system exploiting NIC
- **probability** is a core mechanism for complex systems
  - randomness without any well-defined probabilistic model (distribution) is *not expressive* enough to capture all the properties of complex systems such as biochemical and social systems
  - probabilistic mechanisms are thus required to enable (possibly simple yet) *stochastic behaviours*

  For the reasons above, NIC primitives should feature some probabilistic semantics, as in the case of *uniform primitives* [31]

It is worth emphasising here that the above mentioned features are issues for NIC in that they represent crucial aspects that requires proper consideration when designing NIC models, but at the same time they are *opportunities* for NIC, as they potentially enable further (and richer) forms of expressiveness.

III. Outlook on Research Trends

In the following section we discuss three research areas in which NIC models either have already shown early promising results, or they are currently under scrutiny by researchers as a promising source of solutions.

A. Simulation

Simulation of complex systems is a multidisciplinary issue ranging from physics to biology, from economics to social sciences. Virtually, no complex system of any sort can be studied nowadays without the support of suitable simulation tools; and, experiments done *in silico* are at least as relevant as those *in vitro* and *in vivo*. Given that interaction is one of the foremost sources of complexity, simulation increasingly amounts to simulating interactions. As a result, simulation platforms and tools are devoting more and more attention and resources to modelling and simulating the coordination rules governing the interaction space of applications.

Therefore, a few research works started considering the option of building simulation frameworks on top of coordination languages and infrastructures, so as to take advantage of their ability to deal with complex interactions elegantly and effectively. For instance, in [32] biochemical tuple spaces [17] are exploited as the core abstraction upon which a simulation tool for simulating intracellular signalling pathways is built [33].

There, the extracellular milieu and intracellular compartments are mapped onto special tuple spaces *programmed* so as to work as *chemical solutions simulators* [34], signalling components such as membrane receptors, proteins, enzymes, and genes map to chemical reactions sets expressed as tuples, signalling molecules, activation, and deactivation signals are represented as reactants and concentrations recorded as tuples in the tuple space.

B. Knowledge-oriented Coordination

Intelligent MAS in *knowledge-intensive environments* (KIE) – as well as complex socio-technical systems, in general – require automatic understanding of data and information [35]. *Knowledge-oriented coordination* exploits coordination abstractions enriched so as to allow for semantic interpretation by intelligent agents [36], [37]. For instance, SAPERE [18] coordination abstractions and *semantic tuple centres* [38] both rely on the semantic interpretation of coordination items.

In KIE scenarios explicit search of information is going to become ineffective while the amount of available knowledge grows at incredible rates, thus knowledge should autonomously organise and flow from producers to consumers, in a sort of *knowledge self-organisation* process. MoK (Molecules of Knowledge [39]) is a nature-inspired coordination model promoting knowledge self-organisation, where sources of knowledge continuously produce and inject *atoms of knowledge* in artificial biochemical compartments (analogously to biochemical tuple spaces), knowledge atoms may aggregate in *molecules* and diffuse, knowledge producers, managers, and consumers are modelled as *catalysts*, whose workspaces are biochemical compartments, and their knowledge-oriented actions become enzymes influencing atoms aggregation and molecules diffusion. All of this so as to make relevant knowledge spontaneously aggregate and autonomously move towards potentially interested knowledge workers.

C. Complex Systems

Simon argues that [40]

> "by a complex system I mean one made up of a large number of parts that *interact* in a non simple way."

Some "laws of complexity" exist that characterise any complex system, independently of its specific nature [41]: however, the precise source of what all complex systems share is still in some way unknown in essence. We argue that *interaction* – its *nature*, *structure*, *dynamics* – is the key to understand some fundamental properties of complex systems of any kind.

The above considerations are apparent, i.e., in the field of *statistical mechanics*, where introducing interaction among particles structurally changes the macroscopic properties of the system, along with the mathematical ones. In fact, interacting systems in statistical mechanics are systems where particles do not behave independently of each other, thus the probability distribution of an interacting system does not factorise anymore.

In computer science terms, an interacting system is *non-compositional* [2].

1) Sociotechnical Systems: Nowadays, a particularly-relevant class of complex systems is represented by *socio-technical systems* (STS) [42]. There, active components are mainly represented by *humans*, yet interaction is almost-totally regulated by the *software infrastructure*, where *software agents* often play a key role. Examples of such a kind of systems are social platforms such as Facebook [43] and LiquidFeedback [44], but also urban transportation networks, the ICT infrastructure supporting rescue operations, e-government platforms enabling citizens to participate in local administrations' decision making, and, essentially, any kind of CSCW system [45].

It has already been recognised that such a sort of systems may look at nature seeking for solutions [46], mostly because two foremost characteristics provide opportunities for successfully applying NIC: **unpredictability** of human behaviour should be accounted for, thus uncertainty of actions' outcomes and of decision making should be taken as the norm, not an exceptional condition; the fact that an **environment** – either computational such as in the case of CSCW platforms, or physical, as for urban traffic management – exists not because engineers designed it, but because it is an essential part of the application domain. Accordingly, NIC already accounts for the conceptual and technical tools to deal with both: probabilistic coordination mechanisms and environment modelling.

2) Cyberphysical Systems: Cyberphysical systems (CPS) integrate computing and communication technologies with monitoring and control of physical devices [47]. Examples of CPS include power grids, medical devices, manufacturing control systems, etc.

The centrality of a suitable and effective approach to coordination in such a sort of systems has been already recognised [48], and mostly stems from the need to ensure some crucial features in face of distribution and uncertainty of real-world deployments: dependability, reliability, efficiency—to mention a few. Also, the opportunity to resort to NIC has already been considered [49], [50].

3) The Internet of Things: The Internet of Things (IoT) vision lies somewhat at the crossroad between CPS and STS: whereas is true that strictly speaking the IoT deals primarily with interconnecting devices, it is also true that IoT platforms are in their very essence CPS where the devices and the software running in them are mostly indistinguishable, and that IoT devices are to be used and monitored by human users, exploiting them to augment their capabilities. It is thus possible to apply in IoT scenarios the same approaches we mentioned in the previous sections.

Nevertheless, the peculiarities of the IoT application domain allows for developing ad-hoc models and for undertaking specific approaches to NIC. In [51], for instance, the authors take inspiration from natural metaphors to propose a decentralised service composition model based on *artificial potential fields* (APFs). APFs are digital counterparts of gravitational and magnetic potential fields which can be found in the physical world, and are exploited to lead the service composition process through the balance of forces applied between service requests and service nodes. The applicability of the proposed approach is discussed in the context of dynamic and personalised composition of an audio-visual virtual guide service in an IoT network of a trade show venue.

D. Challenges

Many technical challenges are ahead for those who intend to advance the state-of-art in NIC. Instead of just listing them all, in the following we aim at discussing the two main conceptual challenges that we believe are fundamental to drive research on the topic in a focussed and pragmatic way:

- understanding the basic elements of **expressiveness** is crucial to determine to what extent NIC can cope with real-world problems, by understanding the *minimal set* of coordination primitives required to design complex stochastic behaviours. For instance, *uniform coordination primitives* – that is, LINDA-like coordination primitives returning tuples matching a template with a uniform distribution [52] – seemingly capture the full-fledged dynamics of real chemical and biological systems within the coordination abstractions
- engineering unpredictable systems around **predictable** abstractions is fundamental to ensure the predictability of given MAS properties within generally-unpredictable MAS. In fact, since coordination abstractions are often at the core of complex MAS, making the coordinative behaviour predictable makes it possible in principle to make the overall system *partially predictable*.

We believe in fact that only through a deep understanding of how the core mechanisms of NIC influence system evolution research on NIC will enable engineers to consistently design and build predictable yet stochastic systems.

IV. Conclusion

Gathering ideas and results from the many research fields dealing with complexity emphasises the central role of *interaction*. Since *coordination models* are meant to provide the conceptual framework to express interaction in parallel, concurrent, distributed systems, they are fundamental in order to deal with complexity in computational systems.

In the last decades *nature-inspired coordination models* worked as powerful sources of inspiration for abstractions and mechanisms aimed at harnessing complexity in distributed, pervasive, intelligent systems. In particular, nowadays application scenarios – such as knowledge-intensive environments, socio-technical systems, and the Internet of Things – are going to propose novel noteworthy challenges that are likely to push research on NIC models to its limits and beyond.

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