Coordination of Large-Scale Socio-Technical Systems: Challenges and Research Directions

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***Abstract*—Most of the emerging software-intensive systems nowadays are very large-scale ones, and inherently socio-technical. In this position paper, we argue that the peculiar features of such emerging systems (up to millions of interacting components, lacking central control, mixing humans and artificial components) call for novel approaches to coordinate the overall activities and functionalities. Accordingly, we discuss the key challenges to be faced by research in coordination models and technologies, and try to sketch some promising research directions.**

I. Introduction

The massive diffusion of networked ICT devices increasingly entangled with our physical and social world, along with progresses in the area of robotics and AI, are making our everyday life and economic activities increasingly dependent on the functionalities of large-scale distributed software-intensive (i.e., heavily relying on software) systems [1]. In the near future, our streets will be populated by self-driving cars interacting with traffic control infrastructures, most physical work activities will be performed by robots, citizens will actively contribute to the automated activities of urban management, all health care activities and infrastructures will be managed by intelligent information infrastructure.

All the above examples, and most emerging ICT-centred scenarios, are characterised by the innovative services and functionalities they provide, which require coordination of the activities of distributed components. However, such systems exhibit peculiar traits that heavily challenge most of the coordination models and technologies currently available [2]:

- They require the capability of effectively coordinating the activities of a *huge number* (up to the millions) of *decentralised autonomous* components. This implies the impossibility of enacting some centralised scheme of coordination of the activities, as well as the impossibility of enforcing full control over the activities and interactions of some (if not most) of the components.
- Such systems are inherently *heterogeneous* and *socio-technical* [3], since they require orchestrating the activities of components as diverse as software agents, a variety of sensors and actuators, robots, and – last but not least – they involve the active contributions of humans with their peculiar capabilities and competences [4].
- They are *situated* in dynamic and unpredictable physical and social *environments*, where their components are required to be *context-aware* and *socially-aware* in their interaction, and where consequently any coordination scheme has to be adaptive to the context.

In the reminder of our position paper, we detail some of the above-mentioned emerging large-scale socio-technical scenarios, and discuss their peculiar coordination requirements, and how they call for novel models, languages, and infrastructure (Section II). Then, based on the potential impact of such systems on the area of coordination, we identify some of the new challenges and promising directions for theoretical research and technological development (Section III).

II. Scenarios

The scenarios we outline in this section are generally representative of some easy-to-envision future scenarios, in which millions of ICT sensors, actuators, and services will be called to operate in an orchestrated way, along with the active contribution of the sensing, actuating, and reasoning capabilities of humans [4].

A. Urban Traffic

The role of coordination for handling urban traffic has been widely acknowledged [5]. However, technological evolution mandates for new sorts of coordination models and technologies in the urban traffic scenarios. The drivers that will make urban traffic totally different from what it is now include *(i)* the rise of self-driving cars and *(ii)* the widespread diffusion of on-demand and social mobility services.

First, modern cars already include a number of features to alleviate driver activities (e.g., the capability of autonomously park), and fully autonomous self-driving car is going to hit the streets in a few years [6]. Such self-driving cars will have to coordinate their motion with each other in a cooperative way, and in a (mostly) norm-compliant way with urban computer-based infrastructures such as traffic lights. However, for quite some time, their will also have to interact in a mixed systems of millions of self-driving cars and human-driven ones.

Second, continuous connectivity to the Internet and the rise of social networks are enabling a variety of innovative social mobility models, such as unplanned on-the-fly ride-sharing, dynamic traffic slot allocation, dynamic on-demand schedule of public transport vehicles [7]. The basic idea is to dynamically match the mobility needs expressed by users by coordinating all the actors that can possibly satisfy such needs, in a context-aware way and without neglecting the social aspects involved in the resulting coordination scheme.

B. Robotic and Human Teams

Critical missions such as armed conflicts and handling of natural disasters, which typically involve large teams of soldiers and volunteers, will increasingly involve autonomous weapon systems and robots as well [8], [9]. Autonomous unmanned aerial vehicles and – to some extents – unmanned ground vehicles, are already a reality, and an important support for human teams: many additional classes of robots, there included robotic soldier, are likely to be exploited in the near future.

Accordingly, there will be the need of coordinating the activities of possibly large-scale mixed teams of humans and robots in such critical missions. A key issue for coordination in these scenarios comes from the fact that the activities of the system components are situated in environments and situations that can hardly be known in advance, and therefore require the dynamical adaptation of both individual activities and the coordination schemes required to achieve their effective orchestration.

As a consequence, the scenario requires the adoption of coordination models (and of the corresponding coordination technologies) that could promote the dynamic and adaptive expression of different coordination patterns [10] depending on the situation of the environment.

C. Participatory Urban Management

Municipalities spend a lot of their money in trying to monitor and maintain our urban environments at the best. Activities include: garbage collection, maintenance of roads and public green, installation and maintenance of public lights, etc. Such activities involve a lot of human work – only a small portion of which calls for specialised skills or tools –, are very costly (due to the need of employ a lot of people), are and typically based on static planning.

Clearly, ICT technologies (such as cameras) make it possibile in principle to automate some of the sensing activities, and make them cheaper. However, a more radical evolution that can be promoted by smart phones and continuous connectivity is that of dynamically involving citizens in the above tasks, and make urban management a participatory activity. For instance, one could dynamically involve citizens to help mapping the noise level in a town, by having them supply the lack of appropriate sensors in some parts of the town [11], [12].

Such kind of participatory urban management activities clearly require bringing together the complimentary capabilities of humans and ICT devices, may involve a very large number of devices and humans, and require involving and coordinating humans in a context-aware way, depending on their current positions, goals, and activities.

D. Health Care

Pervasive health care is the new frontier according to a twofold perspective: the adoption of pervasive models and technologies to health care systems, and the ubiquitous availability (everywhere, to everybody) of healthcare [13]. Pervasive health care systems are then typically huge socio-technical systems, where millions of citizens, doctors, and operators need to coordinate through myriads number of interconnected devices, in order to organise health care activities around huge information sources and a wide range of health care hardware, often in critical conditions. Medical protocols need to be enforced, best procedures have to be promoted, whereas emergency operations should be supported in any moment, both on the local and on the global scale.

As a result, coordination in pervasive health care systems generally mandates for robustness, safety, and security: but, first of all, *dependability* and *efficiency* even on the large scale are essential to ensure that critical, possibly unplanned operations can be successfully brought to an end successfully. Also, the ability to deal with a huge and inordinately growing amount of knowledge, and to match it in real time with protocols and procedures is a fundamental requirement of pervasive health care systems, which coordination models and technologies are required to address.

III. Challenges

In this section we analyse some of the peculiar challenges that arise in large-scale socio-technical systems, such as the one exemplified above, and accordingly point out the main research issues that coordination models and technologies are demanded to address in the next years.

A. Human-ICT Coordination

The activities of forthcoming socio-technical systems will involve a variety of agents: humans with mobile devices, ICT sensors and actuators, cameras, self-driving cars, diverse sort of autonomous robots. The features and capabilities of such heterogeneous classes of entities are very different from each other: for instance, one may think at how differently (in terms of modality, timescales, accuracy) humans and artificial vision systems see and classify images, or at how differently robots and humans can assist people.

Accordingly, a coordination language should be expressive enough to enable the representation of coordination schemes among such different classes of components (and, of their associated services and capabilities), yet maintaining a uniform and clear model behind. Similarly, a coordination infrastructure should be able to implement and support such a model in an effective and scalable way, to support the orchestration of myriads of heterogeneous agents physically spread over an urban area. Such issues are so far largely unexplored, and worth being investigated.

B. Autonomy

One key feature of components and systems in nowadays application scenarios is *autonomy*, as clearly exemplified by the current transition from human-driven to self-driving cars. Many different acceptations of the term "autonomy", however, are adopted in different fields – computer science, philosophy, military, psychology, biology, among the many – which lead to different requirements and behaviours for systems and components: and, consequently, for their coordination.

In general, autonomy is typically bound to the existence of an inner goal, to be self-achieved—by the system as a whole, or by the component. Since effective coordination usually requires the mutual understanding of each other goals, the ability to associate actions in a shared environment with their motivating goals seems a relevant feature for coordination models, nowadays. This holds in particular for socio-technical systems, where humans may easily exhibit mixed, hidden, and even unaware goals, whereas artificial components could be either *goal-driven* or *goal-oriented*, according to their goal being implicitly or explicitly represented, respectively [14].

On the one hand, models of coordination supporting goal / plan exchange exist (e.g., [15]), but are often too specific to be adopted as general-purpose coordination models. On the other hand, general-purpose coordination models do not account for goals anyway expressed, nor for their association with coordinated activities. As a result, a first challenge for innovative coordination models and technologies will be to deal with the expression of components' goals, with their association with component's activities, and their visibility/hiding in a shared environment.

More generally, coordination models will be required to deal with large numbers of components of many sorts, featuring many diverse sorts of autonomous behaviours [16]—as such, with largely different coordination needs.

C. Context-awareness and Self-organisation

When it comes to coordinating the activities of large-scale decentralised systems of heterogeneous components situated in dynamic and unpredictable environments, nature may have something to teach us [17]. In fact, many large-scale natural systems that exhibit seemingly goal-oriented behaviours [18], achieve them by relying on self-organising coordination schemes that are inherently adaptive, as well as capable of tolerating dynamic environment and unpredictable contingencies.

In the past few years, we extensively investigated the possibility of exploiting nature-inspired approaches as a means to enable self-organising coordination in context-aware and situated pervasive computing systems [19]. In the context of the EU project SAPERE, for instance, we developed a novel coordination model based on distributed tuple spaces, relying on a simple set of nature-inspired coordination laws [20], [21].

However, despite the encouraging results achieved by the SAPERE project, what is still missing is a real assessment of whether nature-inspired coordination model can support the inherent heterogeneity of the emerging systems, and whether they can really scale to support millions of components and large-scale decentralised scenarios. Attacking such an issue would represent a very promising research direction.

D. Incentives for Participation

A key assumption of most coordination models and languages is that the coordinated components are under the control of engineers, and willing to be coordinated. However, when components belong to multiple stakeholders, or, when such components are humans expected to deliver some service, the effectiveness of the coordination scheme is also related to the effectiveness in incentivising components to participate in the coordination scheme and deliver the necessary services on need.

As far as human are involved, recent work on persuasive technologies analyses how to induce specific behavioural changes and persuade people to establish a desired behaviour [22]. We expect persuasive technologies will be an integral part of future coordination models infrastructure: nevertheless, understanding which forms such technologies could take in a model, and how they could be integrated in a coordination middleware is still an open, yet promising, research direction.

In any case, there could always be specific classes of services and behaviours for which persuasive technologies can hardly apply—e.g., convincing people to park farther than they would autonomously do, in order to provide for a better overall parking availability; or, convincing the owner of a robot to lend it for some time. Therefore, a coordination model should account for more explicit means to incentivise participation, such as monetary rewards or social rewards [23]. However, since the sustainability of such mechanisms and their general effectiveness in coordinated systems is far from having been assessed, there is plenty of room for research in these directions.

E. Economic Dimension

The emergence of cloud computing has clearly pointed out how the economic dimension of contemporary ICT services cannot be ruled out even from models. On large-scale socio-technical systems, money is no longer a secondary concern, which could be deferred after the system design and development: every minimal shift in the costs could produce huge unbalancing in the overall sustainability of systems. And, the availability of certain actions in in given situations is often bound to some measure of cost—differently expressed when actions are by humans (which are typically directly liable for costs) or by ICT components (which are more easily not directly liable)

As far as coordination is concerned, cost issues have generically often been included among the concerns: however, the economic dimension has rarely been explicitly considered. Accordingly, a promising direction for research on coordination is to design models and technologies that explicitly include the economical concerns, possibly associating both individual actions (by either humans or artificial agents) and coordinated activities to their costs (either actual or putative), and making it possible to express coordination policies in terms of economic issues.

F. Knowledge Intensive Environments

The vast availability of data, information, and knowledge, along with their strong dynamics (e.g., data streams) is a typical feature of nowadays complex systems—in particular, large-scale socio-technical systems, where millions of humans and software agents interact by exploiting and exchanging huge amounts of data and information. On the one hand, both human and ICT agents in socio-technical systems typically work as powerful knowledge sources, accumulating and sharing information and data, and act according to knowledge and beliefs, both owned by individuals and shared. On the other hand, shared environments where coordination activities take place are typically knowledge-intensive environments, so that both individual actions and social activities also depend on the amount, sort, and accessibility of data and information in the shared environment [24], [25].

This is why innovative coordination models and technologies will be more and more required to deal with large amount of information and data, to provide support for knowledge modelling and representation, to promote knowledge-rich interactions, and to express knowledge-dependent coordination policies.

IV. Conclusions

In this position paper we argue that the peculiar features of emerging socio-technical software-intensive systems – up to millions of decentralised situated components, lacking central control, mixing humans and ICT components – call for innovative coordination models and technologies. Accordingly, we discuss the key challenges to be faced by researchers in the area of coordination, and accordingly sketch promising research directions.

As a part of our current research, we are working on nature-inspired coordination models and languages [20], [17], which we consider as a promising approach to tackle the identified challenges.

References

[1] M. Wirsing, J.-P. Banatre, M. Hölzl, and A. Rauschmayer, Eds., *Software-Intensive Systems and New Computing Paradigms: Challenges and Visions*, ser. Lecture Notes in Computer Science. Springer, 2008, vol. 5380.

[2] A. Omicini and M. Viroli, "Coordination models and languages: From parallel computing to self-organisation," *The Knowledge Engineering Review*, vol. 26, no. 1, pp. 53–59, Mar. 2011.

[3] N. R. Jennings, L. Moreau, D. Nicholson, S. D. Ramchurn, S. J. Roberts, T. Rodden, and A. Rogers, "Human-agent collectives," *Communications of the ACM*, vol. 57, no. 12, pp. 80–88, Dec. 2014.

[4] F. Zambonelli, "Toward sociotechnical urban superorganisms," *IEEE Computer*, vol. 45, no. 8, pp. 76–78, 2012.

[5] S. Ossowski, *Co-ordination in Artificial Agent Societies. Social Structures and Its Implications for Autonomous Problem-Solving Agents*, ser. Lecture Notes in Artificial Intelligence. Springer, 1999, vol. 1535.

[6] G. J. Offer, "Automated vehicles and electrification of transport," *Energy & Environmental Science*, vol. 8, no. 1, pp. 26–30, 2015.

[7] A. Sassi and F. Zambonelli, "Coordination infrastructures for future smart social mobility services," *IEEE Intelligent Systems*, vol. 29, no. 5, pp. 78–82, 2014.

[8] S. Kohlbrecher, A. Romay, A. Stumpf, A. Gupta, O. von Stryk, F. Bacim, D. A. Bowman, A. Goins, R. Balasubramanian, and D. C. Conner, "Human-robot teaming for rescue missions: Team ViGIR's approach to the 2013 DARPA robotics challenge trials," *Journal of Field Robotics*, 2014.

[9] N. Schurr, J. Marecki, M. Tambe, and P. Scerri, "Towards flexible coordination of human-agent teams," *Multiagent and Grid Systems*, vol. 1, no. 1, pp. 3–16, 2005.

[10] G. Cabri, N. Capodieci, L. Cesari, R. De Nicola, R. Pugliese, F. Tiezzi, and F. Zambonelli, "Self-expression and dynamic attribute-based ensembles in SCEL," in *Leveraging Applications of Formal Methods, Verification and Validation. Technologies for Mastering Change*, ser. Lecture Notes in Computer Science, vol. 8802, 2014, pp. 147–163.

[11] S. Hachem, A. Pathak, and V. Issarny, "Service-oriented middleware for large-scale mobile participatory sensing," *Pervasive and Mobile Computing*, vol. 10, pp. 66–82, 2014.

[12] E. D'Hondt, J. Zaman, E. Philips, E. G. Boix, and W. De Meuter, "Orchestration support for participatory sensing campaigns," in *2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 2014, pp. 727–738.

[13] I. Korhonen and J. Bardram, "Guest editorial: Introduction to the special section on pervasive healthcare," *IEEE Transactions on Information Technology in Biomedicine*, vol. 8, no. 3, pp. 229–234, 2004.

[14] C. Castelfranchi, A. Cesta, R. Conte, and M. Miceli, "Foundations for interaction: The dependence theory," in *Advances in Artificial Intelligence*, ser. Lecture Notes in Computer Science. Springer, 1993, vol. 728, pp. 59–64.

[15] D. Ancona, V. Mascardi, J. Hubner, and R. Bordini, "Coo-AgentSpeak: Cooperation in AgentSpeak through plan exchange," in *3rd International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2004)*, Jul. 2004, pp. 696–703.

[16] S. Mariani, A. Omicini, and L. Sangiorgi, "Models of autonomy and coordination: Integrating subjective & objective approaches in agent development frameworks," in *Intelligent Distributed Computing VIII*, ser. Studies in Computational Intelligence, L. Braubach, D. Camacho, S. Venticinque, and C. Bădică, Eds., vol. 570. Springer International Publishing, 2015, pp. 69–79, 8th International Symposium on Intelligent Distributed Computing (IDC 2014), Madrid, Spain, 3-5 Sep. 2014. Proceedings.

[17] A. Omicini, "Nature-inspired coordination for complex distributed systems," in *Intelligent Distributed Computing VI*, ser. Studies in Computational Intelligence, G. Fortino, C. Bădică, M. Malgeri, and R. Unland, Eds., vol. 446. Springer, 2013, pp. 1–6.

[18] V. Parunak, "Go to the ant: Engineering principles from natural multi-agent systems," *Annals of Operations Research*, vol. 75, pp. 69–101, 1997.

[19] F. Zambonelli and M. Viroli, "A survey on nature-inspired metaphors for pervasive service ecosystems," *Journal of Pervasive Computing and Communications*, vol. 7, pp. 186–204, 2011.

[20] F. Zambonelli, A. Omicini, B. Anzengruber, G. Castelli, F. L. DeAngelis, G. Di Marzo Serugendo, S. Dobson, J. L. Fernandez-Marquez, A. Ferscha, M. Mamei, S. Mariani, A. Molesini, S. Montagna, J. Nieminen, D. Pianini, M. Risoldi, A. Rosi, G. Stevenson, M. Viroli, and J. Ye, "Developing pervasive multi-agent systems with nature-inspired coordination," *Pervasive and Mobile Computing*, vol. 17, pp. 236–252, Feb. 2015, Special Issue "10 years of Pervasive Computing" in Honor of Chatschik Bisdikian.

[21] F. Zambonelli, G. Castelli, L. Ferrari, M. Mamei, A. Rosi, G. Di Marzo Serugendo, M. Risoldi, A.-E. Tchao, S. Dobson, G. Stevenson, Y. Ye, E. Nardini, A. Omicini, S. Montagna, M. Viroli, A. Ferscha, S. Maschek, and B. Wally, "Self-aware pervasive service ecosystems," in *Proceedings of the 2nd European Future Technologies Conference and Exhibition 2011 (FET 11)*, ser. Procedia Computer Science, E. Giacobino and R. Pfeifer, Eds., vol. 7. Budapest, Hungary: Elsevier Science B.V., 4–6 May 2011, pp. 197–199.

[22] B. Fogg, *Persuasive Technology: Using Computers to Change What We Think and Do*. Morgan Kaufmann, Dec. 2002.

[23] O. Scekic, H.-L. Truong, and S. Dustdar, "Incentives and rewarding in social computing," *Commun. ACM*, vol. 56, no. 6, pp. 72–82, Jun. 2013.

[24] S. Mariani and A. Omicini, "Molecules of Knowledge: Self-organisation in knowledge-intensive environments," in *Intelligent Distributed Computing VI*, ser. Studies in Computational Intelligence, G. Fortino, C. Bădică, M. Malgeri, and R. Unland, Eds., vol. 446. Springer, 2013, pp. 17–22.

[25] ——, "MoK: Stigmergy meets chemistry to exploit social actions for coordination purposes," in *Social Coordination: Principles, Artefacts and Theories (SOCIAL.PATH)*, H. Verhagen, P. Noriega, T. Balke, and M. de Vos, Eds., AISB Convention 2013, University of Exeter, UK, 3–5 Apr. 2013, pp. 50–57.