Logic-based Technologies for Multi-agent Systems: Summary of a Systematic Literature Review

JAAMAS Track

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ABSTRACT

The paper summarises a *systematic literature review* (SLR) over *logic-based technologies for MAS.*

KEYWORDS

SLR, Logic-based Technologies, MAS

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1 INTRODUCTION

Precisely when the success of artificial intelligence (AI) sub-symbolic techniques makes them be identified with the whole AI by many non-computer-scientists and non-technical media, symbolic approaches are getting more and more attention as those that could make AI amenable to human understanding. Given the current status of AI technologies – mostly focussed on sub-symbolic approaches successful in well-delimited application scenarios –, a key issue for intelligent system engineering is *integration* of the diverse AI techniques: in software engineering terms, not just how to integrate diverse technologies, but also how to preserve *conceptual integrity* when highly-heterogeneous approaches – bringing about manifold abstractions of various nature – are put to work together.

The most straightforward and generally-acknowledged way to address the above issue is by using *agents* and *multi-agent systems* (MAS). Agents and MAS have been at the core of the design of intelligent systems since their very beginning: their long-term connection with *logic-based technologies* might open new ways to engineer *explainable intelligent systems*.

This is why understanding the current status of *logic-based technologies for MAS* is nowadays of paramount importance and why our work focus on logic-based approaches in MAS: they are to be counted among the most promising techniques for building understandable and explainable intelligent systems. Furthermore, given the unavoidable push towards the exploitation of intelligent applications, focussing on logic-based *technologies* is of strategical importance. Accordingly, understanding and representing the current status of the available logic-based MAS technologies is a key step – from both an historical and an avant-garde perspective – to let MAS researchers and practitioners identify the actually usable methods for the engineering of intelligent systems.

To this end, in [7] we provide a Systematic Literature Review (SLR) driven by the primary research question: “What is the role played by logic-based technologies in MAS nowadays?”. In particular, the SLR aims at understanding which and how many logic-based technologies for MAS can be considered ready enough to face the challenges of modern and future intelligent systems, other than identifying what is missing and what research directions require further attention. Accordingly, the goal is to provide an exhaustive assessment of the available logic-based technologies for MAS, by performing a carefully-designed SLR on the subject.

Method

The SLR follows a well-founded, understandable, and reproducible method defining how to find, include/exclude, and analyse papers describing logic-based MAS technologies. It relies on the standard SLR method: we carried out a manual retrieval, filtering, analysis, and categorisation of huge number of papers, by repeating 8 queries on 6 search engines (Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink, DBLP, ACM Digital Library) and 5 specific conference/workshop proceedings. To keep a tight focus on the *reproducibility* of the whole process, the methodological approach, and the inclusion/exclusion and analysis criteria are carefully designed and described in detail. In particular, we only included works defining or exploiting some *logic-based MAS technology*. A specific definition of *logic-based MAS technology* is provided as well, explicitly requiring the provable availability of *(i)* a clearly identifiable logic-based MAS-related framework into the literature, and *(ii)* some actual software reification of that framework.

Out of the retrieves papers, we selected 271 documents and there identified 47 technologies, classified them according to both a MAS and a logic perspective, and analysed from the technology viewpoint. Accordingly, the technologies selected in our SLR are analysed and assessed from two different perspectives – namely, the MAS and the logical perspective –, thus discussing the specific MAS- and logic-related aspects defined, tackled, or exploited by

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each technology. Along the MAS perspective, we categorise the selected technologies w.r.t. the main MAS abstractions they relate to—agents, societies, environment. Along the logic perspective, we categorise the selected technologies w.r.t. the sort of logic they relate to—thus choosing among first-order logic, description logic, BDI logic, etc. Such categorisations reveal an uneven distribution of logic-based technologies along both MAS abstractions and logics, and highlighting research opportunities on abstractions and logics which are currently in an urgent need of technologies—such as the environment abstraction and the defeasible logic.

We also perform a technical assessment of each technology, according to number of technological criteria including, but not limited to, *(i)* source-code organisation, *(ii)* maintenance status, *(iii)* target platform(s), *(iv)* availability of executable as well as documentation, *(v)* some technical assessment involving the run of executables and available examples. Arguably, the analysis enables a detailed discussion on the current state of logic-based MAS technologies—in particular highlighting their state of maintenance. More precisely, we consider technologies as unmaintained based on the last provable edit involving either the technology source code or any of its software artefacts.[1]

2 MAIN OUTCOMES

The outcome of the SLR highlights that, as far as logic-based technologies for MAS are concerned, there is still room for technological advancements—except for a few relevant success stories. In fact, despite the enormous technological effort clearly carried out by the MAS community in the last decades, several surveyed technologies cannot be considered as mature and ready for use in the new challenging contexts required by AI. Several technologies are in fact unmaintained, outdated, or just proof of concepts.

In our original work the discussion attempts to provide a comprehesive answer to all the SLR research questions. In the following we summarise some general remarks in relation to key features of modern intelligent systems, namely:

(i) inherent distribution and decentralisation and deep intertwist with domains like the Internet of (Intelligent) Things (Io(I)T) and Cyber-Physical Systems (CPS);

(ii) support to key properties such as robustness, efficiency, interoperability, portability, standardisation, situatedness, and real-time support;

(iii) need to reconcile and synthesise symbolic and sub-symbolic AI, exploiting the former to *explain* the latter so as to overcome fears and ethical issues posed by AI by providing for explainability, observability, interpretability, responsibility, and trustability—the scope of XAI [1].

Applicability to distributed domains such as IoT and CPS. The existing agent-oriented logic-based solutions applicable to the IoT and CPS are only available for a specific and limited set of devices and platforms. For instance, Agent Factory Micro Edition (AFME) [9] enables the execution of a deliberative agent on top of mobile phones with CLDC/MIDP profiles and Sun-SPOT sensor by means of TCP/IP and Zigbee protocols.

However, some technologies, more than others, are explicitly designed to support IoT domains and CPS. For example, the LPaaS architecture [5] is designed to promote distributed intelligence for the IoT world—offering logic programming as a service, and explicitly addressing the requirements and issues of cloud and edge architectures. Analogously, the situated coordination approach promoted by the TuCSoN/ReSpecT model and technology can be explicitly exploited to handle situatedness in MAS as a coordination issue. Also, TuCSoN [11] provides the main abstractions for IoT environments: environmental resources can be sources of perceptions (like sensors), targets of actions (like actuators), or even both.

Finally, there are technologies that are not explicitly meant to address the IoT and CPS domains, but still let us suppose they would be easily portable to those domains—because of their standard compliance, interoperability, and portability features. Among the many, Jason [3] supports interoperability with non-Jason agents via JADE [2] through FIPA-ACL communication [8]. Similarly, there are extensions to JACK [12] that make it work in open systems. Finally, the Teleo-Reactive [10] approach has been often exploited to facilitate the development of the IoT systems as a set of communicating Teleo-Reactive nodes.

Symbolic and sub-symbolic integration. With respect to the need to reconcile and integrate symbolic and sub-symbolic techniques, none of the selected technologies has been experimented yet [6], due to their original design purpose out of this scope. However, we argue that portable and interoperable technologies might be more suitable for the integration. Anyway, the field is still unexplored and represents a frontier research domain.

Can existing technologies be labelled as ready? If not, what is missing? The role of logic-based technologies in MAS nowadays exhibits a huge potential for covering the vast majority of intelligent system abstractions. However, just a few among the technologies surveyed can be actually labelled as *ready-to-go*, in particular when considering the new challenges for symbolic technologies in AI.

Even though 10% of the selected technologies can be considered as mature – in terms of cross-platform support, code quality, and ease of distribution in heterogeneous environments –, most of the times they have not been tested in pervasive and real-world scenarios, yet. This implies, at least, that further research and technical activity are required to ensure that any technological barrier can be overcome. Furthermore, integration with sub-symbolic techniques remains a *nice-to-have* feature, but it is not actually a thing in any MAS technology, for the time being. Nevertheless, the selected technologies are an excellent starting point for *(i)* highlighting the advantages of logic-based technologies, and *(ii)* broadening the scope of research towards the directions envisioned.

In the end, we forward the interested readers to the original SLR for the full details [7].

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[1]Since our original assessment (September 2020), some technologies described as unmaintained reworked their repositories, code and/or documentation—as in the case of DALI (https://github.com/AAAI-DISIM-UnivAQ/DALI) and MCAPL (https://autonomy-and-verification.github.io/tools/mcapl).

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