Introduction to the Special Issue on Distributed Hybrid Systems

Alessandro Abate
University of Oxford, UK

Uli Fahrenberg
EPITA Research Laboratory (LRE), Paris, France

Martin Fränzle
Carl von Ossietzky Universität Oldenburg, Germany

This special issue contains seven papers within the broad subject of *Distributed Hybrid Systems*, that is, systems combining hybrid discrete-continuous state spaces with elements of concurrency and logical or spatial distribution. It follows up on several workshops on the same theme which were held between 2017 and 2019 and organized by the editors of this volume.

The first of these workshops was held in Aalborg, Denmark, in August 2017 and associated with the MFCS conference. It featured invited talks by Alessandro Abate, Martin Fränzle, Kim G. Larsen, Martin Raussen, and Rafael Wisniewski. The second workshop was held in Palaiseau, France, in July 2018, with invited talks by Luc Jaulin, Thao Dang, Lisbeth Fajstrup, Emmanuel Ledinot, and André Platzer. The third workshop was held in Amsterdam, The Netherlands, in August 2019, associated with the CONCUR conference. It featured a special theme on distributed robotics and had invited talks by Majid Zamani, Hervé de Forges, and Xavier Urbain.

The vision and purpose of the DHS workshops was to connect researchers working in real-time systems, hybrid systems, control theory, formal verification, distributed computing, and concurrency theory, in order to advance the subject of distributed hybrid systems. Such systems are abundant and often safety-critical, but ensuring their correct functioning can in general be challenging. The investigation of their dynamics by analysis tools from the aforementioned domains remains fragmentary, providing the rationale behind the workshops: it was conceived that convergence and interaction of theories, methods, and tools from these different areas was needed in order to advance the subject.

2012 ACM Subject Classification Computing methodologies → Model verification and validation; Computer systems organization → Embedded and cyber-physical systems; Mathematics of computing → Stochastic processes; Theory of computation → Concurrency; Theory of computation → Distributed computing models; Theory of computation → Logic and verification; Theory of computation → Program reasoning; Theory of computation → Self-organization; Theory of computation → Timed and hybrid models

Keywords and Phrases Distributed hybrid systems

Digital Object Identifier 10.4230/LITES.8.2.0

Acknowledgements The editors acknowledge the *Chaire ISC : Engineering Complex Systems* and École polytechnique, in particular Éric Goubault, for financial support on some of the workshops, out of which this special issue was born, as well as for financing the special issue itself. We also wish to thank the editorial manager Michael Wagner for his excellent work, the authors of the papers in this issue, and the speakers and participants of the three workshops on distributed hybrid systems.

Published 2022-12-07

Editor Alessandro Abate, Uli Fahrenberg, and Martin Fränzle

Special Issue Special Issue on Distributed Hybrid Systems

1 Papers in this special issue

The first paper in this issue, by *Arvind Adimoolam* and *Thao Dang*, lies in the intersection of control theory, hybrid systems, and distributed systems. It is based on the PhD thesis of the first author and on several conference papers of both authors, and builds upon an invited talk by the second author at the DHS 2018 workshop. The work showcases the versatility of complex zonotopes for the analysis of networked control systems. Such systems are subject to network delays, packet dropouts, inaccurate sensing, and quantization errors, all of which have to be taken into account when analysing them. The authors show a result about the existence of complex zonotopic invariants and extend existing algorithms for stability verification of networked control systems.

The second paper, by *Pierre Courtieu*, *Lionel Rieg*, *Sébastien Tixeuil* and *Xavier Urbain*, concerns itself with distributed robotics, an area which itself is in the intersection of control theory and distributed systems. It builds upon an invited talk by the fourth author at the DHS 2019 workshop and presents the Pactole framework for formal modeling and analysis of protocols for mobile robotic swarms. Built on the Coq proof assistant, Pactole provides a uniform modeling language for protocol development which takes into account the many variations between models for distributed robotics and permits to devise certified proofs of possibility and impossibility results.

Article three in this issue, authored by *Uli Fahrenberg*, lies in the intersection of real-time systems and concurrency theory and introduces a new formalism of higher-dimensional timed automata. The interest is in modeling systems which exhibit both real-time behavior and concurrency, which is difficult or impossible in other existing frameworks. The author shows that the standard zone-based methods carry over from timed automata to higher-dimensional timed automata and also extends the model to higher-dimensional hybrid automata.

The fourth paper, by *Eduard Kamburjan*, *Stefan Mitsch* and *Reiner Hähnle*, introduces hybrid active objects for the modeling and analysis of hybrid systems, in order to address the challenges at the intersection of hybrid systems and concurrency. Building upon a talk at the DHS 2019 workshop, the proposed high-level programming-based approach extends the active-objects language ABS with features for modeling hybrid systems. The authors also extend the formal semantics of ABS and its runtime environment and implement a formal verification tool for hybrid ABS.

Article five in this issue, due to *Paul Kröger* and *Martin Fränzle*, builds upon a talk at the DHS 2018 workshop and identifies shortcomings of existing formal models for hybrid systems when it comes to describing the interactive behavior of multiple hybrid-state agents. It demonstrates rigorously that even the most expressive formal models of hybrid-state dynamics cannot precisely cover the emergent joint behavior of rationally acting agents and that existing models are thus bound to either provide significantly pessimistic or significantly optimistic verdicts about the overall system dynamics. Aligned with the overarching goal of developing pertinent theories for the behavioral analysis of distributed hybrid systems, the article proposes a novel model of Bayesian hybrid automata that considerably extends stochastic hybrid automata in order to overcome this deficiency.

The sixth paper, by *Ameneh Nejati* and *Majid Zamani*, concerns itself with networks of stochastic hybrid systems and the construction of control barrier certificates for these. The issue at stake is compositionality, thus, the synthesis of state-feedback controllers for interconnected systems based on certificates computed for subsystems. Building upon an invited talk by the second author at the DHS 2019 workshop, the paper proposes a dissipativity approach which takes into account the structure of the interconnection topology. The authors demonstrate the obtained results on comprehensive case studies.

The final article is titled "Real-Time Verification for Distributed Cyber-Physical Systems" and builds upon a talk at the DHS 2019 workshop. It proposes a real-time decentralised reachability approach for safety verification of a distributed multi-agent CPS, with the underlying assumption that all agents are time-synchronised with a low degree of error. Each agent periodically computes its local reachable set and exchanges this reachable set with the other agents with the goal of verifying the system safety, with local safety verification tasks based on their local clocks by analysing the messages it receives.

2 Conclusion

The fourth workshop on distributed hybrid systems was to be held in Vienna in 2020, associated with the CONCUR conference, but fell victim to the Covid pandemic. Whether the DHS workshop series will be revived in the future, and under which format, is uncertain, so this special journal issue may well be the conclusion of the DHS series.

One may thus rightfully pose the question as to the achievements of the workshops and this special issue, seen as a whole. The first purpose of the DHS workshops was to connect researchers working in real-time systems, hybrid systems, control theory, distributed computing, and concurrency theory, and as this special issue bears witness, that purpose has been achieved.

Another question is whether, through convergence and interaction of methods and tools from these different areas, the workshops have contributed to advance the subject of distributed hybrid systems itself. Many of the papers in this special issue concern themselves with research in the intersection of several of the above-mentioned areas, but it is of course difficult to assess how much the workshops themselves have contributed to these works.

Something that still has to emerge, and perhaps would be too much to expect from just three workshop editions, are new overarching theories which combine the subjects underlying distributed hybrid systems in new ways. The quest for such unifying theories becomes pronounced, given that distributed hybrid systems are at the heart of the recent push towards so-called smart environments, be it "smart cities" as denoting anticipated forms of interconnected intelligent urban structures, or "smart grids", "smart transportation", and "smart health" advancing energy supplies, transportation systems, and medical technology, or "Industry 4.0" revolutionising manufacturing technology. It thus is to be expected that such theories will materialize and will extend and generalize beyond specific domains. The influence of the DHS workshops, which have outlined manifold elements of an overarching theory as witnessed by the articles included in this volume, on the final theories-to-be cannot yet be assessed with full scrutiny.