

Final report for the project

Model Rating: Enhancing model checking with information on model distance

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1 Research activity

The research activity focused on the area of formal methods and its application to Artificial Intelligence (AI).

In particular, we showed how well-known and established techniques from the area of formal verification can be successfully used to address common problems in AI such as temporal datasets evaluation.

Model checking is a technique that makes it possible to verify whether a system complies with a specification. Its typical use allows for a Boolean answer, that is, an affirmative answer if the system conforms the specification, a negative one otherwise. The key idea is to extend such a technique to make it return a more informative output, namely, a degree measure about how bad/good a model of a system is with respect to a specification given in input. Very interestingly, it turned out that such an enhanced model checking technique, which we generally refer to as *model rating*, has applications out of the realm of automated system verification. In fact, we showed that it can be used in typical data mining and AI scenarios: *query evaluation* against a temporal database, *temporal constraint checking*, and as a procedure for *rule evaluation* serving, e.g., as fitting function within evolutionary algorithms for machine learning and classification tools. Our findings have been published in the international conference TIME 2017 [3].

The use of theoretical tools and techniques for practical AI applications gives more relevance and significance to theoretical problems that are otherwise given less attention: when facing a problem from a purely theoretical perspective, one tends to consider the problem in its full generality; however, it makes sense, for several practical applications, to have fast solutions for subclasses of instances. It is the case, for example, with the model checking problem: while model checking has a bad computational behavior in its general formulation (over infinite structures), it makes much sense, for the aforementioned application in AI, to restrict to finite structure to get more efficient model checking algorithms.

In a paper published to ICTCS 2017 [6], we implemented an efficient model checker for interval temporal logic over finite structures.

Following the same research direction, we extended and generalized the ideas presented in [3], and proposed a technique to evaluate interval temporal logic specifications against a finite model, seen as incomplete infinite ultimately periodic models [11]. This approach lends itself to quantitative evaluations as in model rating, as a finite structure can be seen as an incomplete version of several infinite ultimately periodic models, and thus it is possible to establish degrees of reliability based on, for example, how much information the finite, incomplete model carries and how much information must be added to it to get an infinite ultimately periodic model that satisfies a given formula. The outcome of this line of research has been submitted to the top-tier conference in the area of artificial intelligence (AAAI) and it is currently undergoing the revision process [11].

Following other research direction, we have been working on the following topics.

- In the area of planning, we have introduced a bounded version of Timed Propositional Temporal Logic, and we showed that it is expressive enough to capture timeline-based planning with bounded constraints, thus allowing one to use logical machineries to reasoning about planning; our findings appeared on the proceedings of IJCAI 2017 [1], one of the most prestigious conference in AI. We then solved an open problem in the field of timeline-based planning, by proving tight complexity bounds for the timeline-based planning problem in its most general formulation, that is, when both unbounded temporal relations and token durations are allowed; this result is published in the proceedings of KR 2018 [12], another top-rated AI conference.
- In the area of logic for computer science, we studied a qualitative and quantitative extension of the well-known logic ATL for reasoning about multiagent systems [13]; the resulting work is published in the proceedings of AAMAS 2018, the leading conference in the area of agents and multiagent systems.

Moreover, we introduced and studied a prompt extension of the interval temporal logic PNL. The investigation resulted in a paper published in the proceedings of JELIA 2016, a well established international conference on logic in artificial intelligence [5].

- In the area of formal languages, we introduced and studied an extension of omega-regular languages, aiming to filling the gap left from previous extensions; we also gave a translation of such a class of languages into automata and logic; our findings have been published in [4, 7]. Moreover, we have been selected to participate, with an extended version [9] of our paper [7], to the selection process for a special issue of the journal of Theoretical Computer Science, devoted to a selection of the best papers presented at ICTCS 2017.
- In runtime verification, we have been working to lie theoretical foundations for monitoring techniques. A survey has been published in the proceedings of the international conference RV 2017 [2]. The short-term goal is to

develop a technique for combined verification, which combines advantages of model checking and runtime verification.

- As further work, we have completed and submitted extended journal versions of papers previously published to conferences. In particular, we submitted:
 - paper [8] to the journal of Theoretical Computer Science, to be published in a special issue in memory of Maurice Nivat; the paper will be published in 2019;
 - paper [10] to the journal of Information and Computation; the paper is undergoing the revision process.

2 Products of the research

- [1] D. Della Monica, N. Gigante, A. Montanari, P. Sala, and G. Sciavicco. Bounded timed propositional temporal logic with past captures timeline-based planning with bounded constraints. In Carles Sierra, editor, *Proc. of the 26th International Joint Conference on Artificial Intelligence (IJCAI)*, pages 1008–1014, Melbourne, Australia, August 2017. ijcai.org.
- [2] Adrian Francalanza, Luca Aceto, Antonis Achilleos, Duncan Paul Attard, Ian Cassar, Dario Della Monica, and Anna Ingólfssdóttir. A foundation for runtime monitoring. In Shuvendu K. Lahiri and Giles Reger, editors, *Proc. of the 17th International Conference on Runtime Verification (RV)*, volume 10548 of *Lecture Notes in Computer Science*, pages 8–29, Seattle, WA, USA, September 2017. Springer.
- [3] Dario Della Monica, David de Frutos-Escrig, Angelo Montanari, Aniello Murano, and Guido Sciavicco. Evaluation of temporal datasets via interval temporal logic model checking. In Sven Schewe, Thomas Schneider, and Jef Wijsen, editors, *Proc. of the 24th International Symposium on Temporal Representation and Reasoning (TIME)*, volume 90 of *LIPICs*, pages 11:1–11:18, Mons, Belgium, October 2017. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik.
- [4] Dario Della Monica, Angelo Montanari, and Pietro Sala. Beyond ω -regular languages: ω -regular expressions and counter-check automata. In Patricia Bouyer, Andrea Orlandini, and Pierluigi San Pietro, editors, *Proc. of the 8th International Symposium on Games, Automata, Logics and Formal Verification (GandALF)*, volume 256 of *EPTCS*, pages 223–237, Roma, Italy, September 2017.
- [5] Dario Della Monica, Angelo Montanari, Aniello Murano, and Pietro Sala. Prompt interval temporal logic. In *Proc. of the 15th European Conference On Logics In Artificial Intelligence (JELIA)*, volume 10021 of *Lecture Notes in Computer Science*, pages 207–222, 2016. This work was completed before the beginning of this project, but it was presented and published during the first year of this project.

- [6] E. Cominato, D. Della Monica, A. Montanari, and G. Sciavicco. A model checker for interval temporal logic over finite structures. 18th Italian Conference on Theoretical Computer Science (ICTCS), 2017.
- [7] D. Barozzini, D. Della Monica, A. Montanari, and P. Sala. Counter-queue automata with an application to a meaningful extension of omega-regular languages. 18th Italian Conference on Theoretical Computer Science (ICTCS), 2017.
- [8] L. Aceto, D. Della Monica, I. Fábregas, and A. Ingólfssdóttir. When are prime formulae characteristic? Submitted at the journal of Theoretical Computer Science—Special Issue in memory of Maurice Nivat. To appear., 2019.
- [9] D. Barozzini, D. Della Monica, D. de Frutos-Escrig, A. Montanari, and P. Sala. Beyond ω -regular languages: ωT -regular expressions and their automata and logic counterparts. Invited for a Special Issue of the journal of Theoretical Computer Science on a selection of best papers at ICTCS 2018. To be submitted., 2019.
- [10] D. Bresolin, D. Della Monica, A. Montanari, and G. Sciavicco P. Sala. Decidability and complexity of the fragments of the modal logic of allen’s relations over the rationals. Submitted at the journal of Information and Computation. Under review., 2019.
- [11] D. Della Monica, A. Montanari, A. Murano, and G. Sciavicco. Ultimately periodic interval-based model checking for temporal dataset evaluation. Submitted to the 33rd AAAI Conference on Artificial Intelligence (AAAI), 2019.
- [12] D. Della Monica, N. Gigante, A. Montanari, and P. Sala. A novel automata-theoretic approach to timeline-based planning. In *Proc. of the 16th International Conference on Principles of Knowledge Representation and Reasoning (KR)*, 2018.
- [13] D. Della Monica and A. Murano. Parity-energy ATL for Qualitative and Quantitative Reasoning in MAS. In *Proc. of the 17th International Conference on Autonomous Agents and MultiAgent Systems (AAMAS)*, pages 1441–1449, Stockholm, Sweden, 2018.

3 Other activities

Conferences and workshops organization

- PC member of AAMAS 2019
- PC member of AAAI 2019
- PC member of AI*IA 2018
- PC member of CILC 2018
- PC member of GandALF 2018

- PC member of IJCAI-ECAI 2018
- PC Chair of the 32nd Italian Conference on Computational Logic “CILC 2017” (<http://cilc2017.unina.it/>), held in Naples (Italy) on 26-28 September 2017.
- Organizing Committee member of the 18th Italian Conference on Theoretical Computer Science “ICTCS 2017” (<http://ictcs2017.unina.it/>), held in Naples (Italy) on 26-29 September 2017.
- Organizing Committee member of the 1st Workshop on Formal Methods in AI “FMAI 2017” (<https://sites.google.com/site/fmai2017homepage/>), held in Naples (Italy) on 22-24 February 2017.

Research visit

- May 2017: Visiting period for research collaboration *c/o* prof. Adrian Francalanza at University of Malta (Malta).

Talks at international conferences

- “Parity-energy ATL for qualitative and quantitative reasoning in MAS”:
 - conference presentation at AAMAS 2018, Stockholm, Sweden, July 13, 2018,
 - workshop presentation at FMLAMAS 2018, Stockholm, Sweden, July 10, 2018.
- “Prompt Interval Temporal Logic”: conference presentation at JELIA 2016, Larnaca, Cyprus, 11 November 2016.

Review activity

During the 2 years of project I acted as reviewer for the following journals/conferences/workshops:

- conferences/workshops: AAMAS 18, AAMAS 17, CSL 17, FOSSACS 17, ICALP 17, ICTCS 17, IJCAI 17, MFCS 17, TACAS 17;
- journals: IEEE Transactions on Systems, Man and Cybernetics: Systems (SMCA); International Journal of Approximate Reasoning (IJA); Information & Computation (IC); ACM Transactions on Computational Logic (ToCL); Artificial Intelligence (ARTINT); Annals of Mathematics and Artificial Intelligence (AMAI); Acta Informatica.

4 Conclusions and acknowledgments

In conclusion, we want to point out that the career of the recipient of the grant, Dario Della Monica, has largely benefited from the financial support offered by INdAM. During the project period, Dario Della Monica was able to increment his scientific production, and enlarge his connections and expertise. This resulted, *inter alia*, in the following two remarkable achievements that will further boost Dario’s career:

- he got the “abilitazione scientifica nazionale ASN” for “professore di seconda fascia (professore associato)” for SSD ING-INF/05.
- he got a position as Assistant Professor (RTD-A) at Dipartimento di Scienze matematiche, informatiche e fisiche (DMIF) at University of Udine.

The grant recipient is really grateful to INdAM for the valuable and constant support.

Udine, October 30, 2018

Dario Della Monica