Cassting

Deliverable D1.2

Games on Evolving Structures, Interactions with Open Environments

Wolfgang Thomas (RWTH Aachen)

Project	Cassting — Collective Adaptive Systems SynThesIs with Non-zero-sum Games		
Project id.	FP7-601148		
Workpackage	WP1	Nature	R (report)
Deliverable	D1.2	Dissemination	PU (public)
Date submitted	September 2014	Date due	September 2014
Version	1.0 (final)		

SEVENTH FRAMEWORK PROGRAMME

Games on Evolving Structures,
Interactions with Open Environments

Wolfgang Thomas (RWTH Aachen)

September 2014

1 Introduction

The subject of games on evolving structures is still in its beginnings. The conceptual and technical difficulties in this field have their roots in the combination of two aspects: the dynamics involved in the interaction between multiple agents, and the changes given by an evolving game arena. The objectives in such games arise in quite different formats, and the task of "synthesis of strategies" is—as yet—not possible automatically from specifications as it is known from the theory of infinite regular two-player games. The efforts of Cassting aim at a clear advance in the state-of-the-art. We report on four contributions of the Cassting teams in which interesting progress was made, although we are still not in a phase where automatic strategy synthesis with a truly wide scope would be possible.

The teams of Cassting have been active in this area already before the launch of the project, and work described in this report partly builds on this background.

In the Section 2 we recall two basic kinds of games on evolving structures and previous work:

- the sabotage games first devised by van Benthem and further studied (before Cassting) in the Aachen team;
- the connectivity games proposed by the Aachen team.

The subsequent sections present four papers with results obtained in Cassting: Section 3 describes work by the Mons-Brussels team that deals with a quantitative extension of sabotage games. Section 4 is devoted to a novel application of connectivity games that brings together the community of Cassting with network engineering. In Section 5 we report on work of the Aalborg team on dynamic networks of hybrid systems. Finally, Section 6 descibes a result by the Aalborg team on dynamic behaviour of Petri nets with respect to specifications that are game theoretic in nature.

2 Some Background Results

2.1 Sabotage Games

Motivated by frustrations to move as a passenger in the Dutch railway system, van Benthem [vB05] devised a finite game which is specified by a finite directed graph G with designated start vertex s and target vertex t. The player Runner takes a path through G, starting in s and proceeding edge by edge, aiming at reaching t, whereas after each of his moves the player Blocker takes out an edge from G. Runner wins if he has a strategy to reach t whatever choices Blocker takes for eliminating edges. The complexity of solving these finite games was determined by [LR03a], and an in-depth study was given in the dissertation of Philipp Rohde (On games and logics over dynamically changing structures; [Roh05]). A transfer of some of these these results to a probabilistic setting (where Blocker behaves as "nature" according to a probability distribution on the edges) was done in [KRT12]. Work of the Mons-Brussels team described in Section 3 gives algorithmic results on a quantitative extension of this model.

2.2 Connectivity Games

A closely related but conceptually different game-theoretic model for the study of dynamic networks was proposed by [GRT13]; see also the dissertation of Radmacher [Rad12]. (The paper [GRT13] was published during the project time of Cassting but is not listed among the Cassting publications since the actual work was done before Cassting started.)

The model is motivated by communication networks that are subject to failure of nodes and where the restoration needs resources. The corresponding two-player game is played between "Destructor" (who can delete nodes) and "Constructor" (who can restore or even create nodes under certain conditions). As an objective for Constructor the network property to be connected is considered, either as a safety condition or as a reachability condition (in the latter case starting from a non-connected network). The cited work studies the question under which conditions the solvability of the corresponding games for Constructor is decidable, and in this case obtains upper and lower complexity bounds, as well as algorithms derived from winning strategies. It is interesting to note that (due to the asymmetry between the players) safety and reachability objectives are not dual to each other and are treated separately.

This model is motivated by the antagonism between "suppliers" and "users" of a communication network on one side and the generation of faults (either by nature or by malicious interference) on the other. This leads to a concept of *dynamic network games* in which a game position is just given by a current shape of a network. The party that generates faults is modeled by Destructor who can "delete" nodes in a network. The other parties involved are the suppliers of the network and the users. In the cited papers we pursued a view that represents a compromise between conceptual simplicity and adequacy for practical applications, namely by a merge of the two parties suppliers and users in a single player called Constructor. This player has the power to restore deleted nodes or even to create new nodes (i.e., to extend the network beyond its original shape), matching the purpose of a supplier, and she also can transmit information along edges of the network, matching the actions of an user.

The results clarify the solvability of these connectivity games in several versions, complementing a result of [RT08] that the reachability problem (to reach a connected network by Constructor) is undecidable in the cases where the creation of new nodes is allowed. It is shown that for safety games solvability (for Constructor) is undecidable in the general case but – maybe surprisingly – decidable under restrictions for the use of nodes that cannot fail. More results, not mentioned here, are concerned with complexity bounds.

3 A Quantitative Extension of Sabotage Games

The teams of Mons and Brussels have started work on models of quantitative sabotage games. Recall that the sabotage game (Johan van Benthem [vB05]) mentioned above works as follows: Whereas one player (Runner) moves along the edges, the other players takes out a link after each step. Hence, this game is naturally finite, and stops after a bounded number of steps. It has been shown to be PSPACE-complete to solve these games [LR03b] as well as a randomized variant of it [KRT12]. The aim of the present work was to extend the study of sabotage games to deal with behavior of infinite lengths. To that purpose, the process of sabotage has to been changed to incorporate possibly unbounded behaviors. Our choice is to handle this by introducing quantities. Whereas Runner continues to move along the edges, Blocker has now a budget of tokens that he puts on edges of the graphs, and is allowed to move one token at every step. Runner wants to minimize the average or total number of tokens he sees during the whole play. If the budget is fixed a priori, the problem of knowing whether Runner has a strategy to obtain an average value below a given threshold seems to be solvable in polynomial time. However, the dependency in the budget is not clear, and seems exponential a priori. We are seeking for results for this class of games. Special cases already seem difficult but have interesting applications. For instance, the static case, where Blocker simply drops his tokens on the arena and leave them as they are forever is not simple. The previous problem then seems to be a dynamic variant of it that merges the static problem with a kind of "cops and robber game" [ST93].

Our first step to understand better this problem has been to consider classical zero-sum two-player games with a fusion of mean-payoff and reachability objectives. This has proved to be fruitful, even if still far from our original objective. A research report with our first results on these reachability quantitative games is available [BGHM14]. We are continuing with work on the original problem.

Reference: [BGHM14]

4 Guaranteeing Stability in Dynamic Networks

Building on the preparatory work as described above in the section of connectivity games, progress was achieved by the RWTH team in the study of networks with dynamic behavior. The work was done in collaboration with J. Gross (KHT, Sweden), an researcher in communications networks, thus enabling us to create bridges to industrial practice.

This resulted in the paper "Guaranteeing Stability and Delay in Dynamic Networks based on Infinite Games" (S. Tenbusch, J. Gross, C. Löding, F. Radmacher), accepted at IEEE MASS 2014. Here we study stability and delay in dynamic networks under adversarial conditions. Adversarial conditions are mandatory in establishing deterministic performance guarantees in networks. Under this framework, we concentrate on the general stability region for a network, i.e. without specifying the routing algorithm. This is in contrast to related work for adversarial network conditions, where usually the "backpressure routing algorithm" is considered.

Over the last two decades most results on network stability have been established regarding the backpressure routing algorithm as (for example) investigated in an early contribution by [TE92]. It studied network stability under random stochastic arrival processes but with fixed link capacities and showed that under certain conditions on the arrival rate of the flows the network stays stable if backpressure routing is the algorithm for forwarding data between the nodes. Subsequently, further extensions of the stochastic model were investigated. However, most strikingly, from a practical point of view an application or a network provider might be interested in guarantees with respect to stability or the end-to-end delay, which cannot be studied based on stochastic models.

Instead, a more assessable criterium for network stability is of interest: What is missing is a more fundamental insight into the stability region under adversarial conditions.

Our contribution, summarized in the four items below, resolves this issue by a novel methodology.

1. We present an infinite games based model which is used to analyze adversarial dynamic networks under critical and subcritical load. This modeling and analysis method is completely different to the usual analysis technique for network stability, where the drift of backlogged queues is considered.

2. Based on this approach we obtain conditions for network stability, as well as a bound on the number of packets in dynamic networks for critical load. These conditions essentially define the network stability region under adversarial conditions regardless of the routing scheme.

3. Furthermore, we provide a delay bound for dynamic networks under subcritical load.

4. Finally, we present an algorithm that checks given instances of dynamic networks for stability. While our theoretical results indicate that exponentially many network conditions need to be considered in the worst case

to determine network stability, we present a backtracking approach which considers only a tiny fraction of these conditions for rather practical instances. This leads in a numerical example to quite acceptable run times.

Reference: [TLRG14]

5 Dynamic Networks of Hybrid Systems

The Aalborg team addressed the problem of enhancing the tool UPPAAL-SMC by features that allow users a dynamically modify a network of timed automata on the fly—by creating new templates. Also a logic supporting queries about such templates has been devised. The work has been integrated into UPPAAL tool suite.

In more detail: The statistical model checking engine in UPPAAL has been extended to support the analysis of stochastic hybrid systems with respect to temporal properties expressed in a weighted extension of Metric Interval Temporal Logic (MITL). UPPAAL-SMC now supports the analysis of dynamic networks of stochastic hybrid systems. In particular, this engine has been applied to efficiently determine (Pareto-) optimal parameter settings of parameterized controllers. Finally, initial steps have been taken toward applying statistical model checking to synthesize near-optimal strategies for stochastic timed games

The modelling formalism for dynamic networks of stochastic hybrid automata is based on primitives for the dynamic creation and termination of hybrid automata components during the execution of a system. It is founded on the basis of timed input- output (IO) transition systems. The formalism operates on a collection of timed IO-transition systems (templates) that can be instantiated during transitions of active templates. The templates could be generated by any model with semantics given as timed IO-transition system but in our implementation we rely on Hybrid Automata. In this way we allow for natural modelling of concepts such as multiple threads found in various programming paradigms, as well as the dynamic evolution of biological systems.

We provide a natural stochastic semantics of the modelling formalism based on repeated output races between the dynamic evolving components of a system. As mentioned, the specification language is a quantified extension of the logic Metric Temporal Logic (MTL). As a main contribution, the statistical model checking engine of UPPAAL has been extended to the setting of dynamic networks of hybrid systems and quantified MTL. The main difference from MTL is the addition of two operators, one to quantify on the (unknown) number of components of the network, and another to reason on arithmetic operations on this number. We demonstrate the usefulness of the extended formalisms in an analysis of a dynamic version of the well-known Train Gate example, as well as in natural monitoring of a MTL formula, where observations may lead to dynamic creation of monitors for sub-formulas.

In future work on this topic, the team will consider also dynamic channel creation and extending UPPAAL with this feature.

The current implementation is to be considered as a preparation work on defining timed automata models with dynamic behaviour. Extending it to UPPAAL TIGA (games on dynamically changing structures) is planned too.

Reference: [DLLP13]

6 Process Creation in Petri Nets

Another recent work of the Aalborg team is concerned with timed-arc Petri nets—a model which supports in their bounded version the creation of (a limited number of) new parallel processes. An unbounded monotonic subclass of these nets (with unbounded process creation) is defined where we show decidability of strong soundness. In the unbounded case, it is a little bit surprising as reachability for this monotonic subclass is undecidable but soundness is decidable. Soundness is captured by a condition that involves alternating reachability (from each reachable marking we can reach some final marking). This alternation can be explained also as a simple game when one player is trying to bring a system into a certain configuration and then the second player should continue the execution and prove that from this configuration a final configuration can be reached. The algorithms were implemented in our tool TAPAAL (`http://www.tapaal.net`) and publicly released in June 2014.

The motivating context of this work is the adequate modelling of workflow processes.

Workflow nets were introduced by Wil van der Aalst as a formalism for modelling, analysis and verification of business workflow processes. The formalism is based on Petri nets abstracting away most of the data while focusing on the possible flow in the system. Its intended use is in finding design errors like the presence of deadlocks, livelocks and other anomalies in workflow processes. Such correctness criteria can be described via the notion of soundness that requires the option to complete the workflow, guarantees proper termination and optionally also the absence of redundant tasks. After the seminal work on workflow nets, researchers have invested much effort in defining new soundness criteria and/or improving the expressive power of the original model by adding new features and studying the related decidability and complexity questions.

Quantitative aspects like timing are of interest in numerous time-critical applications. The workflow model considered here is based on timed-arc Petri nets where tokens carry timing information and arcs are labelled with time intervals restricting the available ages of tokens used for transition firing.

We study the foundational problems of soundness and strong (time-bounded) soundness. We explore the decidability of these problems and show, among others, that soundness is decidable for monotonic workflow nets while reachability is undecidable. For general timed-arc workflow nets soundness and strong soundness become undecidable, though we can design efficient verification algorithms for the subclass of bounded nets. Finally, we demonstrate the usability of our theory on the case studies of a Brake System Control Unit used in aircraft certification, the MPEG2 encoding algorithm, and a blood transfusion workflow. The implementation of the algorithms is freely available as a part of the model checker TAPAAL.

Reference: [MSS14]

7 Conclusion

The progress reported in this deliverable is of course moderate, but internationally visible, addressing quite diverse aspects of the research theme, and definitely moving towards the aims of Cassting.

Whereas the four Cassting publications mentioned below were mostly written in separate Cassting teams, several results would not have been possible without the Cassting cooperation (e.g., between the teams of Aachen, Mons, and Brussels). Moreover, the exchange of results in the preparation of the present deliverable has opened new tracks of cooperation. Finally, despite the diversity of models addressed here, some interesting general insights came out of these research activities, for example that reachability and safety objectives are not dual to each other and may share quite different algorithmic properties.

List of Cassting Publications

[BGHM14] Thomas Brihaye, Gilles Geeraerts, Axel Haddad, and Benjamin Monmege. To reach or not to reach? Efficient algorithms for total-payoff games. Research report 1407.5030, arXiv, 2014.

[DLLP13] Alexandre David, Kim G. Larsen, Axel Legay, and Danny Bøgsted Poulsen. Statistical model checking of dynamic networks of stochastic hybrid automata. In Steve Schneider and Helen Treharne, editors, *Proceedings of the 13th International Workshop on Automated Verification of Critical Systems (AVOCS'13)*, volume 10 of *Electronic Communications of the EASST*, Guildford, UK, September 2013. EASST.

[MSS14] José Antonio Mateo, Jiří Srba, and Mathias Grund Sørensen. Soundness of timed-arc workflow nets. In Gianfranco Ciardo and Ekkart Kindler, editors, *Proceedings of the 35th International Conference on Applications and Theory of Petri Nets (ICATPN'14)*, volume 8489 of *Lecture Notes in Computer Science*. Springer, June 2014.

[TLRG14] Simon Tenbusch, Christof Löding, Frank Radmacher, and James Gross. Guaranteeing stability and delay in dynamic networks based on infinite games. In Habib M. Ammari, editor, *Proceedings of the*

11th IEEE International Conference on Mobile Ad hoc and Sensor Systems (MASS'14). IEEE Comp. Soc. Press, October 2014.

References

[GRT13] Sten Grüner, Frank G. Radmacher, and Wolfgang Thomas. Connectivity games over dynamic networks. *Theoretical Computer Science*, 493:46–65, 2013.

[KRT12] Dominik Klein, Frank G. Radmacher, and Wolfgang Thomas. Moving in a network under random failures: A complexity analysis. *Science of Computer Programming*, 77(7-8):940–954, 2012.

[LR03a] Christof Löding and Philipp Rohde. Solving the sabotage game is PSPACE-hard. Technical Report AIB-05-2003, RWTH Aachen, 2003.

[LR03b] Christof Löding and Philipp Rohde. Solving the sabotage game is PSPACE-hard. In Branislav Rovan and Peter Vojtás, editors, *Proceedings of the 28th International Symposium on Mathematical Foundations of Computer Science (MFCS'03)*, volume 2747 of *Lecture Notes in Computer Science*, pages 531–540. Springer, 2003.

[Rad12] Frank G. Radmacher. *Games on dynamic networks: routing and connectivity*. PhD thesis, RWTH Aachen University, 2012.

[Roh05] Philipp Rohde. *On games and logics over dynamically changing structures*. PhD thesis, RWTH Aachen University, 2005.

[RT08] Frank G. Radmacher and Wolfgang Thomas. A game theoretic approach to the analysis of dynamic networks. *Electronic Notes in Theoretical Computer Science*, 200(2):21–37, 2008. Proceedings of the First Workshop on Verification of Adaptive Systems (VerAS 2007).

[ST93] Paul D. Seymour and Robin Thomas. Graph searching and a min-max theorem for tree-width. *Journal of Combinatorial Theory, Series B*, 58(1):22–33, 1993.

[TE92] L. Tassiulas and A. Ephremides. Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks. *IEEE Transactions on Automatic Control*, 37(12):1936–1948, 1992.

[vB05] Johan van Benthem. An essay on sabotage and obstruction. In Dieter Hutter and Werner Stephan, editors, *Mechanizing Mathematical Reasoning, Essays in Honor of Jörg H. Siekmann on the Occasion of His 60th Birthday*, volume 2605 of *Lecture Notes in Computer Science*, pages 268–276. Springer, 2005.