THE EXTENDED HOA FORMAT FOR SYNTHESIS

A PREPRINT

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ABSTRACT

We propose a small extension to the Hanoi Omega-Automata format to define reactive-synthesis problems. Namely, we add a “controllable-AP” header item specifying the subset of atomic propositions which is controllable. We describe the semantics of the new format and propose an output format for synthesized strategies. Finally, we also comment on tool support meant to encourage fast adoption of the extended Hanoi Omega-Automata format for synthesis.

Keywords Temporal synthesis · Reactive synthesis · Omega-regular languages · Omega automata

1 Introduction

The field of formal verification has studied several forms of model checking of reactive systems [1, 2]. Model checking essentially asks whether a model of a system satisfies a specification given in some formal logic, e.g. linear temporal logic (LTL). Reactive synthesis, or the automatic synthesis of a reactive system from its specification, goes a step further by completely circumventing the design of a system and its modelization. The earliest version of the synthesis problem was stated by Alonzo Church [3]. Since then, several versions of it arising from different specification formalisms and implementation restrictions have been studied.

The reactive synthesis competition (SYNTCOMP [4] for short) was started in 2014 by R. Bloem and S. Jacobs to collect benchmarks and provide an objective comparison of the state-of-the-art synthesis tools. Initially, the competition consisted of a realizability and a synthesis track for safety specifications. The realizability track just asks whether a system satisfying a given specification exists while the synthesis track asks for it to be output by the tool if it exists.

Synthesis from LTL. Since 2016 tracks with LTL (given in the TLSF [4] format) specifications were introduced. Currently, the synthesis problem for such specifications is usually done in two steps: First, the LTL specification is translated into a deterministic infinite-word automaton. Second, a game is played on the automaton between the controller and its environment. A strategy for the controller in such a game corresponds to an implementation which satisfies the LTL specification.

Synthesis from automata. While the Hanoi Omega-Automata (HOA) format [5] has arguably helped LTL-to-automata translation tools become objectively comparable, the same has not yet occurred for game-solving tools aimed at solving LTL synthesis. Furthermore, when comparing LTL-synthesis tools, it is not clear at which one of the aforementioned steps they excel. This is why in this document we propose an extension of the HOA format which allows to directly encode games played on automata.

1See http://www.syntcomp.org/
2 Input format

The Hanoi Omega-Automata (HOA) format is a format to describe finite-state automata that accept (as their language) sets of infinite words. Such an automaton $A$ is a tuple $(Q, q_0, \mathcal{P}(AP), \Delta, Acc)$ where

- $Q$ is a finite set of states,
- $q_0 \in Q$ is an initial state,
- $AP$ is a finite set of atomic propositions and the alphabet $\mathcal{P}(AP)$ of the automaton consists of their valuations,
- $\Delta \subseteq Q \times \mathcal{P}(AP) \times Q$ is the transition relation, and
- $Acc \subseteq (Q \cdot \mathcal{P}(AP))^\omega$ is an acceptance condition, i.e. a set of infinite runs of the automaton which are considered accepting.

The language of the automaton is defined as usual: the set of words for which the automaton has an accepting run.

2.1 Original format

The original HOA format was described in a CAV’15 paper [5]. More information, as well as Java and C++ parsers for the format, can also be found in the website http://adl.github.io/hoaf/.

Every HOA-format file is split into a header and the body of the automaton. The body encodes all the transitions $\Delta$ of the automaton $A$. The header gives meta-information regarding, amongst others, how $Acc$ is given. Importantly, it also holds information about the atomic-proposition set $AP$.

Atomic propositions. One of the header items is $AP$. This item gives the number of atomic propositions followed by a space-separated list of unique names for each atomic proposition. These are double-quoted valid C-strings and implicitly numbered, starting from 0, from left to right.

Acceptance condition. In the HOA format, information about the acceptance condition is given in two parts. First, an acceptance-condition name is given in the form of a string. Second, a Boolean combination of conditions over acceptance sets gives the actual acceptance condition. Each transition can belong to several acceptance sets. Much like in Muller automata [6], the acceptance condition then specifies which runs are considered accepting by indicating which combinations of finitely and infinitely appearing acceptance sets are “good”. For instance,

“transitions from the first acceptance set can only appear finitely often and transitions from the second acceptance set must appear infinitely often.”

2.2 Extension for synthesis

In the context of reactive synthesis it is necessary to make a distinction between controllable and uncontrollable atomic propositions. That is, the propositions whose value is set by the uncontrollable environment and those whose value is set by the controller. We propose a very simple extension of the HOA format, based on the synthesis extension of AIGER [7], to make this distinction explicitly. We shall add a header item with the following specification

\[ \text{header-item ::= "controllable-AP:" INT* | ...} \]

In other words, the new header item will have a list of space-separated integer indices. These indicate which atomic propositions from the $AP$ header item are controllable. All other atomic propositions are implicitly assumed to be uncontrollable.

3 Semantics: Games played on automata

We now present the formal semantics of the synthesis problem when the input specification is given in the form of an automaton. For convenience, we assume that we are given a deterministic automaton $A = (Q, q_0, \mathcal{P}(AP), \delta)$. Hence, $\delta$ can be thought of as a function $\delta : Q \times \mathcal{U} \times \mathcal{C} \rightarrow Q$, for $\mathcal{U}$ and $\mathcal{C}$ valuations of the uncontrollable and controllable sets of atomic propositions respectively.

\(^2\)For clarity, we are focusing on edge-labelled automata. However, the HOA and extended HOA formats support state-labelled automata as well.
A game. The game we describe is played by a controller and its environment for an infinite number of rounds. In every round, the game starts from a state $q \in Q$. The environment chooses a valuation $u \in U$, followed by a choice of valuation $c \in C$ made by the controller. The round then ends with an update of the current state from $q$ to $\delta(q, u, c)$. The initial state is $q_0$ and the play is winning for the controller if and only if an accepting run of $A$ was constructed.

Formally, a strategy of the controller is a function $\sigma : (Q \cdot \mathcal{P}(\mathcal{AP}))^* \cdot Q \times U \rightarrow C$ mapping the observed sequence of states and atomic-proposition valuations to a valuation of the controllable propositions. The strategy is winning if and only if all plays consistent with it yield an accepting run of $A$.

Realizability and synthesis. Given an automaton as input, the realizability problem asks whether there exists a winning strategy for the controller. The synthesis problem further asks for the winning strategy itself to be output if it exists.

For a more detailed description of the reactive synthesis problem and the game-theoretical approach to solving it we refer the reader to [8, 2].

3.1 A note on non-determinism

Note that giving one of the players the power to resolve the non-determinism does not, in general, yield a correct algorithm [9]. Indeed, when the input automaton $A$ is non-deterministic then the game has to be formalized in a more general way: The game played between the controller and its environment is actually a Gale-and-Stewart game [10] whose winning condition for the controller is the language of $A$. The game solver must either determinize the given automaton or implement some algorithm that deals with the non-determinism explicitly.

4 Output format

A strategy of the controller can be encoded in the original AIGER format [11]. All the uncontrollable atomic propositions should become inputs of the encoded sequential circuit and all the controllable inputs should become outputs. Latches can be used to encode further information such as the states of the input automaton.

4.1 Why two formats?

We could have chosen to encode strategies as automata in the HOA format, just like the input automata. Nevertheless, in the spirit of this track representing an intermediate step in the LTL-synthesis pipeline, we believe having an output format which matches that of the LTL tracks is beneficial for the competition. It is also easier for people to adopt tools participating in this new track and integrate them with an LTL-to-automaton tool to obtain a toolchain comparable to tools participating in the LTL-synthesis tracks.

5 Restrictions for the first edition

In the context of SYNTCOMP 2020, we will restrict the benchmark set to deterministic and complete parity automata only.

For parity automata in the HOA format, the acceptance condition is given via two parameters: $m \in \{\text{max}, \text{min}\}$ and $p \in \{0, 1\}$. Additionally, the transitions of the automaton are assumed to be labelled by natural numbers. For every run, we then consider the set $\text{Inf}$ of transition labels appearing infinitely often. According to the parity acceptance condition, the run is accepting if and only if

$$m(\text{Inf}) \equiv p \pmod{2},$$

e.g. the maximal label appearing infinitely often is even.

6 What about the PGSolver format?

The PGSolver collection of solvers and benchmarks provides a useful framework to test and compare parity-game algorithms. To streamline the adoption of the extended HOA format for synthesis, we provide a simple transformation from it to the PGSolver format.
The \texttt{hoa2pg} tool is a simplified version of one of the components present in a prototype synthesis tool which translates linear temporal logic into a parallel composition of several parity games \cite{Bruyere2019}. In essence, it translates an extended-HOA automaton into a parity game using binary decision diagrams to abstract the atomic-proposition valuations labelling the transitions of the original automaton and by adding intermediate vertices representing the choices of the environment. \texttt{hoa2pg} can be directly used to obtain a realizability solver together with a PGSolver-format parity-game solver.

**Synthesis.** As the transformation abstracts away the atomic propositions, synthesis of strategies in the AIGER format is less straightforward and may require modifying \texttt{hoa2pg} to output more information about the translation into the PGSolver format.

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\footnote{Available from \url{https://github.com/gaperez64/hoa-tools}}