LTL$_f$ Synthesis Under Environment Specifications

Antonio Di Stasio

Sapienza University of Rome, Italy

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Reactive Synthesis

Given a specification φ over inputs $\mathcal{I}$ and outputs $\mathcal{O}$, expressed in:

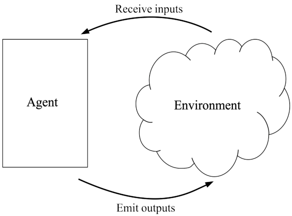
LTL (Pnueli 1977) or LTL$_f$ (De Giacomo, Vardi 2013)

Syntax:

$$\varphi ::= a \mid \varphi \wedge \varphi \mid \neg\varphi \mid \bigcirc\varphi \mid \varphi\,\mathcal{U}\,\varphi \mid \Diamond\varphi \mid \Box\varphi$$

Semantic:
A trace $trace$ is an infinite (LTL) or finite (LTL$_f$) sequence over $\mathcal{I}$ and $\mathcal{O}$. We write $trace \models \varphi$ to mean that τ satisfies φ.

Reactive Synthesis



Agent and Environment Strategies, and Traces

For an agent strategy $\sigma_{ag} : \mathcal{I}^+ \rightarrow \mathcal{O}$ and an environment strategy $\sigma_{env} : \mathcal{O}^* \rightarrow \mathcal{I}$, the trace

$$trace(\sigma_{ag}, \sigma_{env}) = (i_1 \cup o_1), (i_2 \cup o_2) \ldots \in 2^{\mathcal{I} \cup \mathcal{O}}$$

denotes the unique trace induced by both σ_{ag} and σ_{env}.

Synthesis Problem

Given an LTL/ LTL$_f$ task $Goal$ for the agent

Find agent strategy σ_{ag} such that $\forall \sigma_{env}.trace(\sigma_{ag}, \sigma_{env}) \models Goal$

Planning (or Synthesis with a model of the world)

Domain

- Planning consider the agent acting in a **(nondeterministic) domain**
- The domain is a **model of how the world** (i.e. the environment) works
- That is, it is a **specification of the possible environment strategies**

$$[[Dom]] = \{\sigma_{env} | \sigma_{env} \text{ compliant with } Dom\}$$

Planning in nondeterministic domains

Given an task $Goal$ for the agent, and a domain Dom modeling the environment

$$\text{Find agent behavior } \sigma_{ag} \text{ such that } \forall \sigma_{env} \in [[Dom]].trace(\sigma_{ag}\sigma_{env}) \models Goal$$

Environment Specifications

Which kinds of environment assumptions can the agent make?

- Nondeterministic planning domains;
- Forms of fairness ($\Box\Diamond\phi$) and stability ($\Diamond\Box\phi$)[ZhuDeGiacomoPuVardiAAAI2020];
- Safety properties [DeGiacomoDiStasioPerelliZhuKR2021];
- GR(1) formulas [DeGiacomoDiStasioTabajaraVardiZhuIJCAI2021];
- ..

Environments Specifications as LTL formulas

A natural generalization is to consider general environment specifications expressed as arbitrary LTL formulas [DeGiacomoDiStasioVardiZhuKR2020].

Synthesis Under Environment Specifications

Environment Specifications

Let Env be an LTL/LTL$_f$ formula over $\mathcal{I} \cup \mathcal{O}$.

$$[[Env]] = \{\sigma_{env} | \sigma_{env} \text{ satisfies } Env \text{ whatever is the agent strategy}\}$$

Synthesis under environment specifications in LTL/LTL$_f$

Given an LTL$_f$ task $Goal$ for the agent, and an LTL/LTL$_f$ environment specification Env:

$$\text{Find agent strategy } \sigma_{ag} \text{ such that } \forall \sigma_{env} \in [[Env]].trace(\sigma_{ag}, \sigma_{env}) \models Goal$$

Theorem [Aminof et al. ICAPS 2019]

To find agent strategy realizing $Goal$ under the environment specification Env, we can use standard synthesis for

$$Env \rightarrow Goal$$

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LTL_f Synthesis Under LTL Environment Specifications

Problem

Solve the synthesis problem for

$$\varphi^e_{LTL} \wedge \varphi^e_{LTL_f} \rightarrow \varphi^a_{task}$$

separating the LTL_f environment specifications:

$$(\varphi^e_{LTL} \wedge \varphi^e_{LTL_f} \rightarrow \varphi^a_{task}) \iff (\varphi^e_{LTL} \rightarrow \varphi^e_{LTL_f} \rightarrow \varphi^a_{task}) \iff (\varphi^e_{LTL} \rightarrow \neg\varphi^e_{LTL_f} \vee \varphi^a_{task})$$

where $\varphi'_{LTL_f} = \neg\varphi^e_{LTL_f} \vee \varphi^a_{task}$ is expressed in LTL_f and φ^e_{LTL} in LTL.

Key Idea:

1. Agent goal: $\neg\varphi^e_{LTL} \vee \varphi'_{LTL_f}$ — Environment goal: $\varphi^e_{LTL} \wedge \neg\varphi'_{LTL_f}$;
2. Build the DFA of φ'_{LTL_f}, solve the reachbility game for the agent over it;
3. Remove the agent winning area and do the product with the DPA of φ^e_{LTL};
4. Solve the parity games for the environment over it;
5. Combine the two agent winning strategies computed in 2 and 4.

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LTL_f Synthesis Under GR(1) Environment Specifications

Problem

Solve the synthesis problem for

$$\varphi^e_{GR(1)} \rightarrow \varphi^a_{task}$$

Key Idea:

- Agent goal: $\neg\varphi^e_{GR(1)} \lor \varphi^a_{task}$ — Environment goal $\varphi^e_{GR(1)} \land \neg\varphi^a_{task}$
- Build the corresponding DFA $\mathcal{A}_{\varphi^a_{task}}$ of φ^a_{task}, and take its complement $\overline{\mathcal{A}_{\varphi^a_{task}}}$
- Define a $\textsc{gr}(1)$ game whose game arena is $\overline{\mathcal{A}_{\varphi^a_{task}}}$ and winning condition $\varphi^e_{GR(1)}$
- Solve the $\textsc{gr}(1)$ game for the agent, i.e., solve the dual of the $\textsc{gr}(1)$ game.

LTL_f Synthesis Under Safety Environment Specifications

Problem

Solve the synthesis problem for

$$\varphi^e_{\mathcal{S}} \rightarrow \varphi^a_{task}$$

Key Idea:

- Compute the *deterministic safety automaton* $\mathcal{D}$ of $\varphi_{\mathcal{S}}$ (**no Büchi determinization!**)
- Solve the safety game for the environment over $\mathcal{D}$;
- Construct the *maximally permissive strategy* $\mathcal{T}$;
- Build the corresponding DFA $\mathcal{A}_{\varphi^a_{task}}$ of φ^a_{task};
- Do the product of $\mathcal{T}$ and $\mathcal{A}_{\varphi^a_{task}}$;
- Solve the reachability game for the agent over it, and return a strategy, if exists.

LTL$_f$ Synthesis Under Safety Environment Specifications

Problem

Solve the synthesis problem for

$$\varphi^e_{\mathcal{S}} \rightarrow \varphi^a_{task}$$

Key Idea:

- Compute the *deterministic safety automaton* $\mathcal{D}$ of $\varphi_{\mathcal{S}}$ (**no Büchi determinization!**)
- Solve the safety game for the environment over $\mathcal{D}$;
- Construct the *maximally permissive strategy* $\mathcal{T}$;
- Build the corresponding DFA $\mathcal{A}_{\varphi^a_{task}}$ of φ^a_{task};
- Do the product of $\mathcal{T}$ and $\mathcal{A}_{\varphi^a_{task}}$;
- Solve the reachability game for the agent over it, and return a strategy, if exists.

No reduction to the implication!

Future Works

Almost all the techniques are based on the following reduction

Theorem [Aminof et al. ICAPS 2019]

To find agent strategy realizing $Goal$ under the environment specification Env, we can use standard synthesis for

$$Env \rightarrow Goal$$

Possible directions

- In case of safety environment specifications we can directly solve the problem without reduction to the implication.
- What about the other environment specifications? Fairness, $\textsc{gr}(1)$, LTL, ...

Future Works

Almost all the techniques are based on the following reduction

Theorem [Aminof et al. ICAPS 2019]

To find agent strategy realizing $Goal$ under the environment specification Env, we can use standard synthesis for

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Possible directions

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- What about the other environment specifications? Fairness, $\text{GR}(1)$, LTL, ...

Moshe's quote: *"We need to focus on the problems in P, where P does not mean Polynomial Time but* **Practical Problems!"**