Semantic Parsing of Automobile Steering Systems

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ABSTRACT

Formal specification plays crucial roles in the rigorous verification and design of automobile steering systems. The challenge of getting high-quality formal specifications is well documented. This paper presents a problem called 'semantic parsing', the goal of which is to automatically translate the behavior of an automobile steering system to a formal specification written in signal temporal logic (STL) with human-in-the loop manner. To tackle the combinatorial explosion inherent to the problem, this paper adopts a search strategy called agenda-based parsing, which is inspired by natural language processing. Based on such a strategy, the semantic parsing problem can be formulated as a Markov decision process (MDP) and then solved using reinforcement learning. The obtained formal specification can be viewed as an interpretable classifier, which, on the one hand, can classify desirable and undesirable behaviors, and, on the other hand, is expressed in a human-understandable form. The performance of the proposed method is demonstrated with a case study.

Author Keywords

Steering systems, formal specification, signal temporal logic, semantic parsing, reinforcement learning.

ACM Classification Keywords

I.2.6 Learning: Semantic parsing, Reinforcement learning.

INTRODUCTION

Formal specification, a mathematical or logical statement of what a system is supposed to do, plays crucial roles in the rigorous verification and design of automobile steering systems. However, the challenge of coming up with high-quality formal specifications is well documented [7]. For instance, it is not very clear, even for experts, how to construct a set of proper specifications for the vision system used by many autonomous vehicles [6].

We believe that solving the formal specification problem for complex system relies on solving an inverse problem first. Our rationale is that in order for a designer to specify *what a system is supposed to do*, the designer needs to first understand *what the system can do*, particularly when the system is complex. We will call the latter process as 'semantic parsing', the specific goal of which is to automatically translate the behavior of a system into a formal specification. The specification will be 'formal' in the sense that it will be written in some formal language, ideally in temporal logic, such as signal temporal logic (STL) [4], which has been used extensively in the specification of cyber-physical system (CPS). We envision that semantic parsing will enable an interactive process in which a human can inquire a system regarding its capability and eventually the human and the system can work together to come up with an intuitive and at the same time rigorous specification for the system.

a) Related work: Our work is closely related to the problem of requirement mining, which was first proposed in the field of software engineering for legacy code understanding, software maintenance, etc. [1]. In recent years, there has been a surge of interest in requirement mining for CPS [3], particularly those with ML- or AI-based components [6]. Even with all the successes, there are still many fundamental challenges that are unsolved. For instance, all the existing works (with the exception of [5]) assume that the output of the requirement mining problem is a formula φ_θ with a fixed structure but unknown parameter θ. With such an assumption, the requirement mining problem can be transformed into an optimization problem with the goal of finding a parameter θ^* such that φ_{θ^*} optimizes certain cost function, which is usually defined with the concept of *robustness degree* [4]. Obviously, the fixed structure assumption is not that realistic in the sense there needs to be a human domain expert, who ideally should also be knowledgeable of formal language, to prescribe the structure. To make the techniques of requirement mining or semantic parsing more useful and widely adopted, algorithms proposed in [5] provide systematic ways to conduct such a search. But these methods are not efficient. The search order is pre-defined and knowledge gained during the search, e.g., more promising structures vs. less promising ones, is not utilized. This paper will explore a more strategic method by borrowing techniques from nature language processing (NLP) and machine learning (ML).

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b) Contributions: The main contributions of this paper are twofold: *First*, we propose a way of formulating the semantic parsing problem with attribute grammar. Such a formulation subsequently enables us to *strategically* search formula structures by using techniques from NLP. *Second*, to the best of our knowledge, our work is the first instance where the search of logical formulas, in the context of steering system requirement mining or semantic parsing, is conducted by systematically integrating knowledge acquired during the search. We believe that our paper opens the door for the future integration of NLP, ML, and formal methods in CPS.

PROBLEM FORMULATION

In this section, we will first show that signal temporal logic (STL) [4] can be defined with a new formalism called *STL attribute grammar*. We will then present the semantic parsing problem pertaining to this grammar.

STL Attribute Grammar

DEFINITION 1. *The* STL attribute grammar $\mathcal{G}_{\mathcal{STL}}$ *is an attribute grammar* $< V_N, V_T, P, g >$ *with the following specific components:*

- $V_N = \{A, B\}$*, where each element of* V_N *corresponds to an STL fragment (partial formula);*
- $V_T = \{\mu, \Diamond, \Box, \wedge, \vee\}$*, where the meanings of the symbols are predicates, finally, always, conjunction and disjunction, respectively (same with STL);*
- $P = \{P_1, \cdots, P_7\}$*, where the specific production rules are shown in Table 1 (there are five categories of rules, namely* Instance*,* Eventually*,* Always*,* Or*, and* And*);*
- *g maps each node to two types of attributes: (a)* time *attributes that specify the time bounds of the temporal operators used in the node and (b)* predicate *attributes that specify the predicates used in the node. Specifically, the* predicate *attributes includes* signal name*,* comparison operator*, and* constant*. To give an example, for a terminal node* $\mu : x_1 > 1$*, its set of* time *attributes is* $\mu.time = \{\}$*, which is empty, and its set of* predicate *attributes is* $\mu.pre = \{x_1, >, 1\}$ *(we will use the notations .pre and .time throughout the paper). Both types of attributes are synthesized. For instance, production rule* $P_5 : A \to A \vee B$ *indicates that:*

$$\begin{aligned} A.time &= A.time \cup B.time \\ A.pre &= A.pre \cup B.pre. \end{aligned}$$

EXAMPLE 1. *It can be easily seen that an STL formula* $\varphi = \Box_{[0,3]}(\Diamond_{[0,2]}(x_1 > 1) \wedge \Box_{[0,1]}(x_2 < 2))$ *can be derived by following a sequence of production rules* $d = P_3P_7P_2P_1P_5P_1$*, where d is called a* ***derivation****, applied to a set of properly attributed terminal nodes* $V_T = \{\Box_{[0,3]}, \Diamond_{[0,2]}, \mu_1 := (x_1 > 1), \Box_{[0,1]}, \mu_2 := (x_2 < 2)\}$.

Semantic Parsing Problem Formulation

PROBLEM 1. *(Semantic Parsing) Given the STL attribute grammar* $\mathcal{G}_{\mathcal{STL}} =< V_N, V_T, P, g >$*, a positive integer* T*, and two signal sets labeled by a human,* X^+*, the desirable behaviors of a CPS, and* X^-*, the undesirable behaviors of the CPS, find a derivation* d *such that the robustness degree*

$$\rho(X, d) = \min(\min_{x \in X^+}(\rho(x, d)), \min_{x \in X^-}(\rho(x, \neg d))) \qquad (1)$$

is maximized, where (a) $X = X^+ \cup X^-$*, (b)* $\rho(x, d)$ *and* $\rho(x, \neg d)$ *denote the robustness degrees of a signal* x *with respect to the derivations* d *and* $\neg d$*, respectively, and (c)* $|d| \leq T$ *with* $|d|$ *denoting the number of production rules used to generate* d.

Table 1: Production rules of $\mathcal{G}_{\mathcal{STL}}$.

Rule	Category	Notation	Attributes
P_1	Instance	$A\|B \to \mu$	$g(A\|B) = g(\mu)$
P_2	Eventually	$A \to \Diamond A$	$g(A) = g(\Diamond) \cup g(A)$
P_3	Always	$A \to \Box A$	$g(A) = g(\Box) \cup g(A)$
P_4	Eventually	$B \to \Diamond B$	$g(B) = g(\Diamond) \cup g(B)$
P_5	Always	$B \to \Box B$	$g(B) = g(\Box) \cup g(B)$
P_6	Or	$A\|B \to A \vee B$	$g(A\|B) = g(A) \cup g(B)$
P_7	And	$A\|B \to A \wedge B$	$g(A\|B) = g(A) \cup g(B)$

SOLUTION

To solve the semantic parsing problem, two important challenges present themselves: *combinatorial explosion* and *sequential decision process*. To address the *combinatorial explosion* problem, we will first use the idea of *agenda-based parsing* to search possible derivations in a strategic order [2], then re-formulate the agenda-based parsing problem as a Markov decision process (MDP), which enables the utilization of reinforcement learning to deal with issues arising due to sequential decision.

Agenda-based Parsing

Agenda and chart

In order to have a finite words for parsing, we discretize the time bounds and constants in predicates with equal interval. With the discrete time bounds and predicate constants, we can have a finite words, in which each word is a combination of a temporal operator and a predicate, i.e., $\Diamond_{[0,2]}(x_1 > 1)$. An *agenda* Q holds a set of available partial formulas (formula fragments), e.g., $\Diamond_{[0,2]}(x_1 > 1)$ and $\Box_{[0,1]}(x_2 < 2)$. A *chart* H holds the partial formulas that have been used for parsing. In agenda-based parsing, the generation of partial formulas for agenda Q is based on the backbone grammar, $\mathcal{G}_{\mathcal{STL}}$, which uses production rules to specify the possible partial formulas that can be added into the agenda.

The framework of agenda-based parsing is shown in Figure 1, which the agenda-based parsing process is modeled as an MDP. In the beginning, the agenda Q holds a set of partial formulas, and the chart H is empty. Then at each parsing step, the parser, which can be seen as an agent, takes an action by choosing a partial formula, i.e., φ_1, from the agenda, Q, then the evaluation calculates the robustness as the reward. Next, the chosen partial formula is added to the chart, H, and new partial formulas $\Box\varphi_1$, $\Diamond\varphi_1$,$\varphi \wedge \varphi_1$, and $\varphi \vee \varphi_1$ $(\forall \varphi \in Q)$ are generated

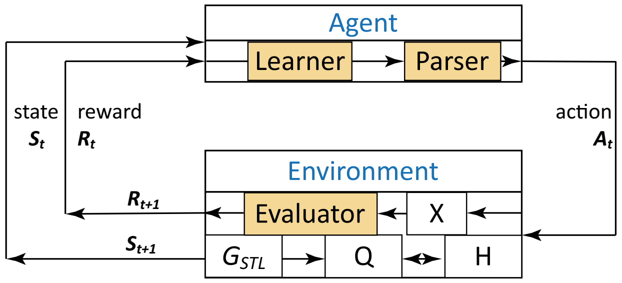
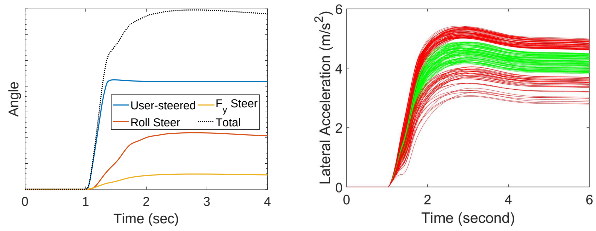


Figure 1: Agenda-based semantic parsing as an MDP.

and added to agenda to create the new state. The parsing process will be continued until a satisfactory formula has been found.

CASE STUDY

In this section, we use our proposed method to parse an automobile steering system of a typical modern mid-size passenger car with 4-corner semi-active suspension shock absorbers (whose effective damping coefficients can be modulated on-the-fly). To mine the specification, which describes the good behaviors for steering test, with the semantic parsing algorithm, a step steering maneuver is chosen (ISO 7401 provides guidance), and several step steer tests are conducted to get a set of multidimensional output signals, denoted as X. For every signal $x \in X$, the lateral acceleration, a_{lat} is one of the dimensions of the x. Then the output signals are labeled by a driver based on user experience, i.e., when the driver thinks the steer experience is good, the output signal is labeled as positive, and vice versa. During the step steering test, an open-loop steering input is used; the final steering angle is first calibrated to the desired output, then the driver has no effect on the results. The input is shown in Figure 2(a) and the label lateral acceleration signals are shown in Figure 2(b).



(a) (b)

Figure 2: (a) The step steering test in steering angular displacement. Note how the total wheel angle setting is a combination of the handwheel input and passive contributions from the suspension (both kinematic an compliant). (b) The set of labeled signals, X, used in the case study. The red and green signals are with bad and good performances, respectively.

Table 2: Number of episodes needed before finding a satisfactory formula with different learning rates and discount factors.

Learning rate α	**Discount factor** γ	**episodes** N	**Robustness** $\rho(X, d)$
10^{-4}	0.95	456	0.1
5×10^{-3}	0.95	564	0.1
10^{-4}	0.8	689	0.1
10^{-4}	0.7	967	0.1

Table 2 shows the number of episodes needed before a satisfactory formula is found for different learning rates and discount factors. The results show that we can always find a satisfactory derivation. i.e., a derivation d is satisfied by all signals in X^+ but violated by all those in X^-. The learning result is as follows:

$$\varphi = \Diamond_{[0,6]}(\Box_{[4.5,6]}(x < 4.6) \wedge \Box_{[4.5,6]}(x > 3.8)).$$

CONCLUSIONS

This paper introduced the problem of semantic parsing for an automobile steering system, which inferred the formal specification of an automobile steering system with a parser. To tackle the combinatorial explosion inherent to the problem, we first formulated the process as an agenda-based parsing process, then as an MDP, and finally used reinforcement learning to solve the problem. The performance of our proposed method was demonstrated with an automobile steering case study.

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