Paper Proposal : Steps towards syntactic and semantic safety guarantees for voice assistants in autonomous vehicles

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Developed with the support of Ekaterina Komendantskaya

1 Abstract

We introduce a grammar for a controlled natural language (CNL) to give imperative commands to an envisioned voice assistant for a self-driving car. The utility of the CNL is that it is inductively defined as a grammar : thereby, the sentences it admits, parsed as Abstract Syntax Trees (ASTs), can be manipulated as mathematical objects amenable to verification techniques. Using the TOUCHDOWN data set to motivate common idioms and phrases our grammar should be capable of parsing, we give a denotional semantics to a subset of Linear Temporal Logic formulas, essentially expressing sequences of states, which are amenable as specifications to downstream applications whose goal is the verification of various aspects of a vehcles behavior. We see this work as a preliminary contribution to a large literature as regards CNLs, verification for natural language-controlled robots, and semantic parsing.

2 Contributions

Initially motivated to give the system assurances against so-called substitution-based attacks, whereby synonyms can be given the same meaning by imposing posterior conditions on the parse trees. Clustering over the tree structure to provide some kind of equivalence to meaningfully similar sentences was an initially enticing direction, as had been done with Komendantskaya and Heras' work on Machine Learning for Proof General (ML4PG) [16]. However, this work had the advantage that there are multiple large, well-maintained Coq libraries which were amenable to clustering, whereby successful results could give rise to use in downstream applications.

Our use case being the design of a non-existent language left us with the conundrum of an impoverished data set to train over and the issue of what utility this would be for downstream applications. What followed may then be seen as a response to these constraints : find a data set suitable to give examples of non-trivial natural language utterances, in addition to finding a suitable semantic langauge with utility and applicability which is amenable to translation from sentences parsed by our grammar.

The primary contributions during this project are as follows :

- A Grammatical Framework (GF) grammar providing the definition of a CNL for directives to a driving agent
- A Haskell mapping trees of our grammar a particulary well-behaved subset of LTL
- An Agda implementation of LTL with a standard semantic interpreation
- A refinement of the TOUCHDOWN Dataset, suited to our needs of designing a better grammar

We suggest that while each of these components are still relatively primitive, they define a pipeline which has potential to provide both theoreitcal insights to researchers and suggest possible practical steps that can be taken to building robust voice appliations in industrial settings. In addition to discussing our own contributions, we try to give a comprehensive literature review that embeds our work in the context of interesting ongoing work happening around the world.

3 Overview

Perhaps the most pervasive question in the use and application of natural language technologies, and one which exemplifies the boundary of the "formalist", verification-minded and "empericst", data-oriented camps in designing such technologies, can be stated as follows : How does one optimize the system to provide for wide coverage of the domain while ensuring that system is robust?

The statistical and machine learning methods applied to Natural Language Processing tasks have made enormous gains over the past three decades. They take a more pragmatic approach : compromise robustness for wide coverage, as this means the tools will be usable and by non-experts, where many believe that the machines should "learn" from us. Somewhat orthogonal,

the formal approaches in computational linguistics, instead, are often more concerned with theoretical justificaiton and explainability. While practical tools are a goal, their practical applications often aren't linguistically informative and therefore they shouldn't override work on building the theoretical models which enable our understanding of the machines. The developers of these theoretically informed systems seek predictable and well-defined behavior for specific problem domains. Yet, these systems fail to generalize without an explosion in complexity when presented with data outside their domain.

Natural language both is structured with respect to rules, admiting lots of predicatbility, yet continuously breaks or introduces exceptions to these rules. This makes it exceedingly hard to penetrate from exclusively the emperical or formalist approach. This leads many to wonder about the degree to which large amounts of data can be augmented with theoretical knowledge about natural language to create optimal and practical systems with respect to both breadth and depth of coverage of language phenomena. The ultimate question seeking compromise from both camps asks : how can we build machines which "understand" us (or at least our data), and which allow us to understand them.

This problem acutely arises in when trying to design a voice assistant in the domain of commanding controllable robots, specifically, autonomous vehicles. For the actions a vehicle takes, mostly the motion and path decisions, must be formally specified or at the very least controlled via some computer system subject to mathematical formalism. Assuming the user directing the vehicle isn't aware of these formalisms, it is incredibly difficult to design a verifiable controller capable of dealing with the breadth of language one may encounter in the wild.

The instructions an arbitrary user gives are not subject to the same formalities the system requires. For her commands may leave out detail ("go into the other lane" with multiple lanes on either side), say something wrong with respect to reality ("go into the other lane" on a single lane road), or give a command the controller should recognize as possible but bad ("drive directly into the car ahead"). Additionally, the controller may need to recognize many ways many users may say "the same thing", that is the same with respect to some semantic formalism. It is obviously worrisome that a nefarious actor may somehow interfere with the controls at any stage, particularly the point at which a linguistic utterance is made, and reassuring one this doesn't happen is critical for such technologies to see adoption. –

We therefore analyze our "big-picture" question above in the following "sub-question" : how can one map the manifold ways of presenting information to an autonomous robot into a rigorous and formally verifiable kernel which the controller can understand? Our proposed solution is to build a semantic parser from natural language commands to Linear Temporal Logic (LTL), whereby we can filter the many possible natural language commands into a "canoncial subset" which are equivalent to (sets of) temporal logic formulas. The "sets of" clause references the inevitable ambiguity of parses even from a big enough parser, even if the size of the canoncial expressions is vastly smaller than the domain of expressions mapping to them.

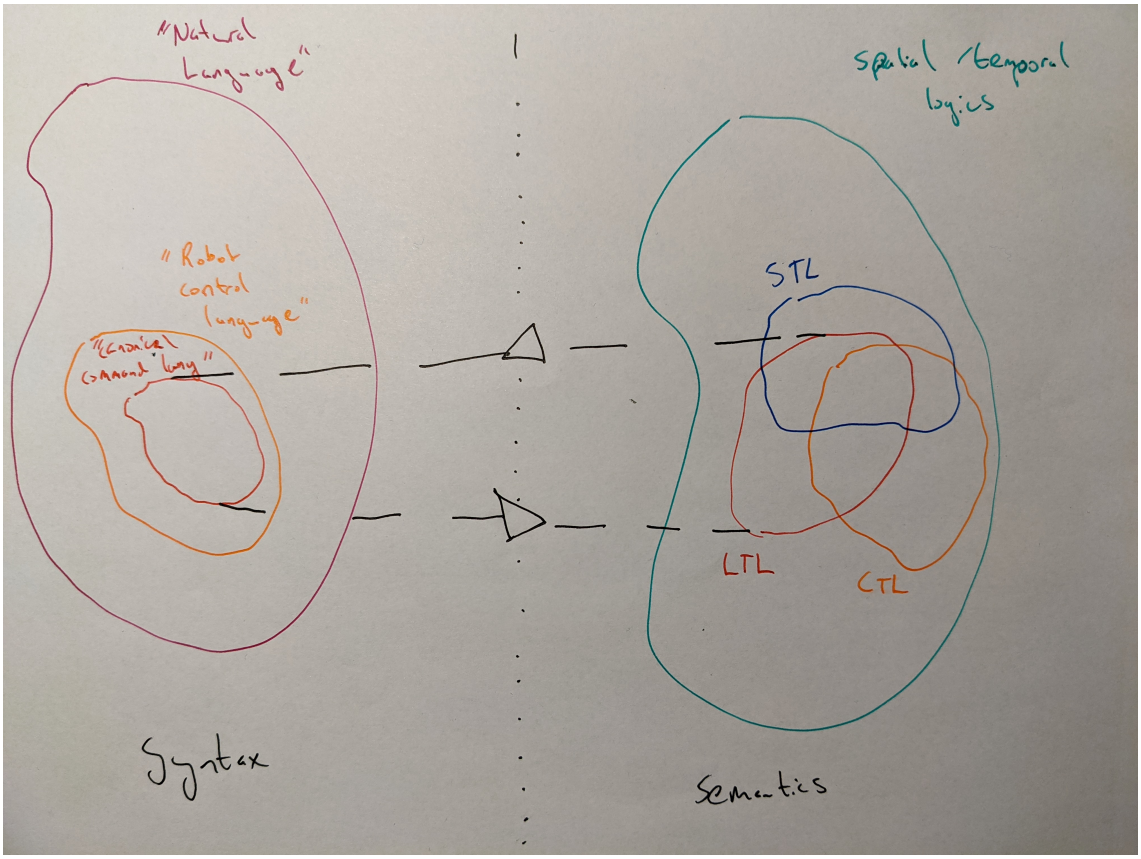

Figure 1: Language and Logical Spaces of Concern

We begin in Figure 1 with a high level overview of this semantic parsing system, whereby the space of natural language syntax can be mapped to some formal language semantic space (and possibly have some kind of inverse mapping). We note that "Natural Language", while an idealized notion, can be thought of the space of interpretable utterances. The relatively small subset of these utterances which one might give to a robot, labeled "Robot Control Language", is the ideal breadth our system would support, is still actually very large. We therefore applying another filter, to the "Canonical Command Language" which is inductively defined via some relatively thin set of grammar rules, which simultaneously generate and parse expressions in some logic. Although we target LTL because of its prominence in the literature and relatively straightforward implementation and interpretation, it should be noted that their are other temporal logics which may well be more expressive and better suited to the actual problem of synthesizing controllers.

Due to the recent influx of transformer based language models like Bert and GPT-3, we take for granted that the easiest way to target our "Robot Control Language" will be through fine-tuning one of these models, as shown in Figure 2. These transformers, trained on a separate corpus like Wikepdia, can be mapped to some suitable set of robot commands, even though these types of expressions will have a sparse presence in the corpus the model was initially trained on (presumably Marco will know more about this than me).

In this context, we can then further refine the language to something less natural, but more well-behaved. The whole proposed pipeline in Figure 3, indicates using the methodology as used in [31], whereby the semantic parser should ideally be able to take any command from the Robot Control Language and turn it into a set of temporal logic formulas, distributed according to most likely interpretation.

Ideally, the downstream dialogue system should either be able to ask for clarification if two formulas are determined to be of some relative likelihood, reject a formula that is not determined

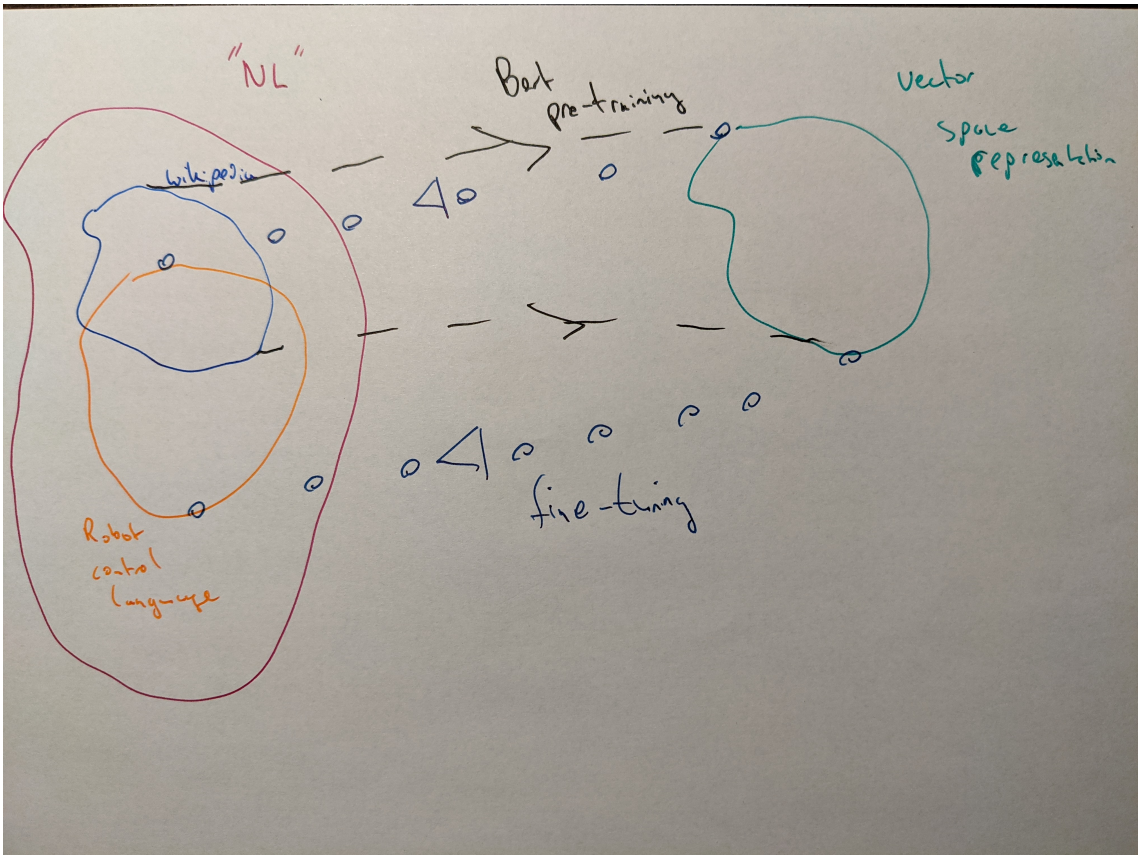

Figure 2: Transformer to Robot Control Language

to be achievable (for whatever reason), or synthesize a sequence of actions (and express those in the CNL) according to the possibly modified current path.

In theory, we can embed clauses which in turn reflect all of natural language : "Stop at the man who is watching the tv show on his phone about time traveler who goes back to the 12th century Mongolia, whereby the man, not speaking Mongolian ..." This is clearly outside the boundary of what the robot control language should support, and ideally would be accepted or rejected by the computer prior to the commands completion depending if there was a man looking at a phone. Our parser currently accepts strings in our primitive canonical language, designed in Grammatical Framework (GF), such as :

```
p "drive to the store , turn right and stop at the dog"

MultipleRoutes And (ConsPosCommand (SimpleCom (ModAction Drive (MkAdvPh To
(WhichObject The Store)))) (BasePosCommand (SimpleCom (ModAction Turn
(WherePhrase Right))) (SimpleCom (ModAction Stop (MkAdvPh At (WhichObject The
Dog))))))
```

However, we may envision our system being able to accept an expression in the Robot Control Language like "hit the petal till we reach the store, hang a right, and halt when you see a cute little puppy". We could certainly adjust our parser to accomodate this, but it would be one of many possible edge cases unlikely to be uttered. To accomodate many more such edge cases would cause an exponential blowup in the parser size (thereby slowing down parsing), but more importantly, cause the programmer a headache in building the parser, and then mapping the NL ASTs to a LTL form. If we treat F as the operating expressing the existence a future state, X as the next state, and G meaning the universal future, our desired LTL formula would

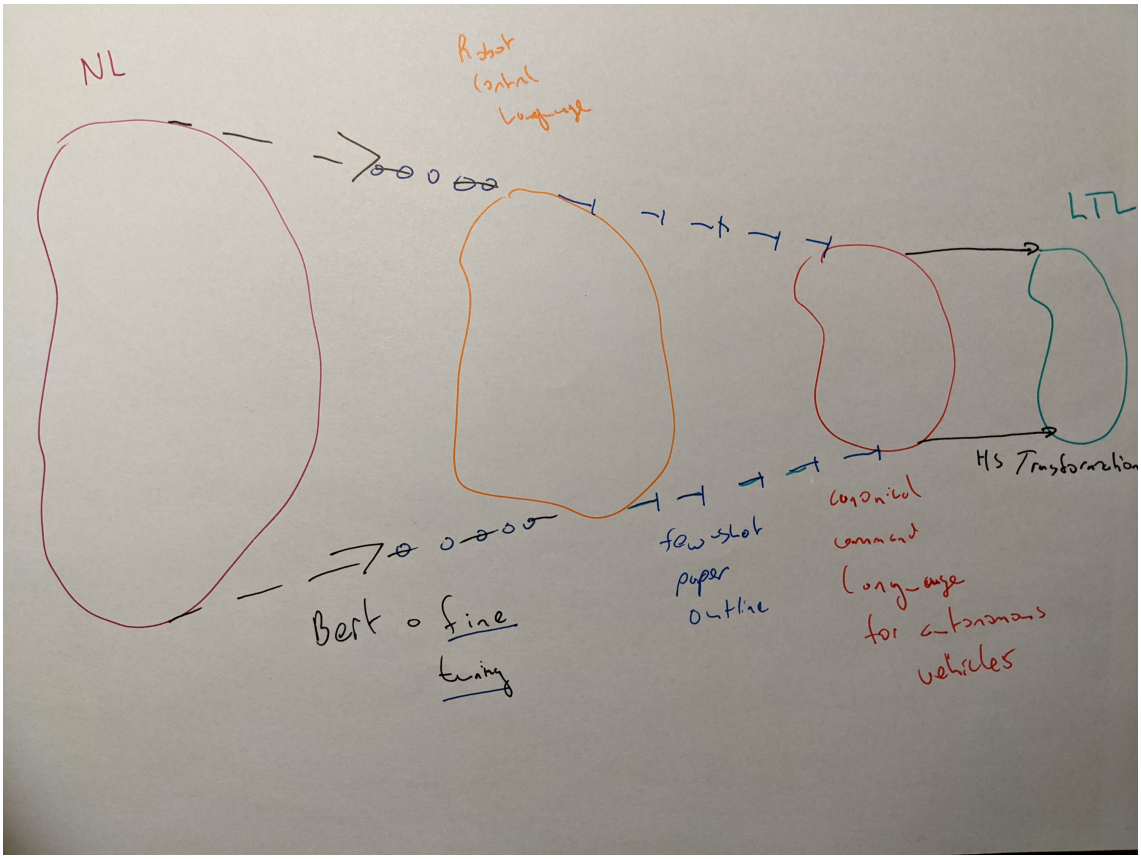

Figure 3: Pipeline from NL to LTL

most likely treat this as $F\ (store \wedge\ (X\ turn\_right\ \wedge\ (F\ (G\ dog))))$, although we propose that the actual grounding of these to images or controllable actions to some downstream system.

LTL has been a popular logic for specifying controllable robot behaviors, particularly with respect to verification of their behaviors. In [28], Rizaldi et al. prove logical correctness of a motion planner with respect to LTL formulas over maneuver automata formulas in the Isabelle/HOL theorem prover, a non-dependent cousin of Agda. We are choosing to deeply embed LTL in Agda for a few reasons, although the syntax of the embedding could easily be translated to any other dependently typed theorem prover, and with a little more effort probably any functional programming language. The composition of a "weakly verified" natural language front-end with a formally verified back-end such as in Rizaldi's work would pave the way for a fully verified, utterance-to-vehicle-path pipeline for the autonomous vehicles.

The big question to address is what kind of verification conditions the natural language component should be subjected to, and what kind of attacks would be most important to preemptively anticipate. Substitution based attacks [30], for instance, have been consistently emphasized throughout our discussions so far. The question is, *where* in the pipeline it would be best to filter out the vulnerabilities, as well as *how*.

One possibility would be to define words modulo equivalent meanings using Wordnet [24] in the syntactic phase, either via training [27] (presumably during the fine-tuning to the Robot Command Language or our "canonicalization" from that). It has been suggested that Bert is already relatively robust against such attacks [13], but we nonetheless feel that even higher sensitivities of robustness may be better done at other phases in the pipeline.

Alternatively, one could just map these equivalent Wordnet forms to equivalent parse trees using the Portable Grammar Format (PGF) Haskell library, which essentially deeply embeds a GF grammar into a Generalized Algebraic Datatype (GADT).

For instance, if we abstract over all abstract syntax trees for our grammar using this library, we can define the following Haskell functions to equate a "female human" with a "woman".

```
treeMapfemalePersonIsWoman :: forall a. Tree a -> Tree a
treeMapfemalePersonIsWoman (GModObj GFemale GPerson) = GWoman
treeMapfemalePersonIsWoman GWoman                    = (GModObj GFemale GPerson)
treeMapfemalePersonIsWoman gp = composOp treeMapfemalePersonIsWoman gp
```

There has been work integrating multiple language Wordnets with GF [33], so it would presumably be easy to integrate with our system, depending on how large we want the grammar to get.

As it is unclear what the best direction for this is, and how the attacker model in the context of an autonomous vehicle might work, all these decisions need to be made in the context of discussions within the group.

[Addendum before meeting :]

The TOUCHDOWN data set [7] seems like the most comprehensive and relevant data we'll find to fine-tune via one of these pre-trained models. Please see https://github.com/lil-lab/touchdown

The idea of domain specific pre-training can be traced to [12], where the authors introduce the concepts of *domain-adpative pretraining* and *task-adpative pretraining*, whereby this additional pre-training phase greatly improves efficacy of the LM on corpus and task data not well represented in the training data.

The language models have been show [18]

3.1 Data Set

The most comprehensive data set known to us is the TOUCHDOWN data set [7], which can simultaneously serve as a data source to inform the actual grammar (ideally, we'd like to be able to generate a grammar from a data source)

authors use "interactive visual navigation environment based on Google Street View"

position of the agent relative to an object, and the position of two objects relative to one another "resolving the spatial descriptions", but we focus only on the navigation part of the task

Positive

- Real-world observations
- Real descriptions of these observations
- Diverse, relatively large
-

Follows "instruction writing, target propagation to panoramas, validation, and workers and qualification", the validation here

That having the data grounded is both incredibly beneficial, but also makes designing the syntax and semantics tricky.

- Finding the touchdown only coarsely approximates general navigating in a city.
- The workers aren't in a place they know, so everything the reference is in their immediate visual environment
- and this is a "short-term" task, it requires no long-distance navigation and reasoning
- Limited to NYC, hectic urban environments (also, daytime)
- Working with panoramas is not necessarily a great simulation to a real environment
- "They are not per- mitted to write instructions that refer to text in the images, including street names, store names, or numbers"
- No temporal reasoning (as spatio-temporal is assumed)

Ideally our data set would then have the properties

- Long and short-term tasks
- Different cities, different languages (this will be dependent on the context of the data collected), for instance, where there are dirt roads
- Updates over time (the user can update a context locally or globally) on the road
- Users with various degrees of contextual information Contextual information - street place, names (named entity recognition) accessible to google - people's names (mom's house)

That the data collection task in an objective way is inherently tied to the way we approximate it in collecting data, thereby limited by our experimental apparatus and assumptions in designing the data set.

What is the actual feasibility of this stuff?

how well does a given logic allow us to reason about a space of instructions. What is the logic grounded to, how it is verified , all of these may effect the choice of formulas

we can't just design a perfect language to capture our meaning - goes back to the wishful thinking of Frege, but we can try to approximate it

next intersection (and next left?) versus next gas station versus "next to" will be a store on your left with stars next to the name.

there is could either be "all of the apartment buildings on your left"

if you are going the correct way. logical content You will know you're on the correct road if to your left there are planters in the middle of the street

3.2 Syntax and Semantics

When designing a grammar, we can pretend that initially

san abstract syntax, we have the following considerations

That when we are conditioning our syntacitc model of emperical, noisy, and biased natural language data, so as to ideally generalize to unencountered phenomena.

A central insight ambiguity :

- Ontological semantic space. What are we trying to represent?
- Intended semantic space, the logical or formal system which our grammar will map to (via Haskell transformations)
- We want to account for some grammatical constructions via the abstract syntax, but outsource most of the grammaticality to the RGL
- Data source. How to conform to the data set in a way that's faithful but doesn't overfit (the overfitting can probably result in generating functions which are useless and either make our parser slow down or overgenerate)

While theres no clear way of relating the trade-offs, we can come up with some heuristics that shed light. Developing the "ontological design" allows one to capture the intuitive problem.

3.3 Ambiguity

What happens when we encounter ambiguity? For instance, in p "go to the person with the dog ." The prepositional phrase "with the dog" can either modify person (as an adjectival clause) or it can modify go (as an adverbial clause). Because the parser is designed to accommodate simple cases of both types of clauses, these ambiguities, even in simple sentences from our corpus, will grow quickly.

In the case of a vehicle, however, knowing the correct parse is dependent on the context in which the driver is going to the person : is the language grounded in the fact that there a dog in the car, or a person in the purview with a dog (or, most confusingly, perhaps both conditions are met, in which case more contextual information is required to disambiguate the correct parse).

For we can actually program the semantics to accommodate both scenarios, whereby $F(manwithdog/\ GFinish)\ F(man/\ GFinish)/\ Gwithdog$

We can define our semantics to accommodate both interpretations, whereby the parses produce unique semantic conditions, and the LTL solver will have to see which condition is more easily satisfied. While this edge case may seem overly pedantic to consider, as one's intuition might suggest the first case to be overwhelmingly more natural, the

We should just make simplifying assumptions, though, at least for the purpose of a grammar like ours.

4 Introduction

While the evaluation of machine learning systems provides assurances using different scores and metrics on different tasks assures one they may on average perform better than humans at certain tasks, the advent of adversarial attacks [32] with the intention of deceiving such a system by a hostile actor leads the system designer to desire, and possible require additional verification about the system's behavior. In the context of natural language processing (NLP), where data sources rely on strings of text, these attacks can focus an array of features from spellings of individual words to rearranging entire sentences []. So-called synonym attacks, which adversarially target the system at the lexical level, can cause traditional NLP models to [...] [].

In the context of designing a voice assistant for an autonomous vehicle, whereby one can give commands like "turn right after the woman with the big dog", we desire that the intensional belief a user has about her utterance is consistent with the extensional behavior of the vehicle. This can be done through an intermediary mapping to a formal semantic representation. Ensuring that the syntactic content of a voice director's (well-formed) utterance maps predictably to the logical form is important from the verificationist perspective : one wants to maximize the "syntactic completeness" of the system [21].

Aside from the user experience being compromised by a system which has been adversarially afflicted, there is also a possibility of physical danger for the passenger and other people in the vicinity. As voice directed robots have many possible points of failure, we focus on two types of verification for our system. Rather than focus on breadth of language coverage, which ML language models excel at of due to their reliance on statistical modeling and tons of data, our system is narrowly focused as a proof-of-concept, from which it could either be extended by hand, or different components modified using other techniques and tools.

5 Current Landscape

5.1 Voice assistants for autonomous vehicles

The public company Cerence [] is already designing voice assistants for autonomous vehicles, for which it has a large software stack between the voice processing to actual control of current automative components. In addition to its technologies, many of which aren't accessible to external researchers due to intellectual property restrictions, Cerence has contracts with large automakers [..]. It is therefore natural to inquire, what a small team with varied backgrounds and not nearly the same expertise nor experience within the technological team at Cerence can provide.

First, we believe that the focus on verification, insofar as we envision it, is unlikely to be of current concern at Cerence due to the fact that their products are still being developed, and the primary goal of producing a working product is likely to precedence over preventing non-existent hostile actors.

Additionally, it is going to have to be determined by [verification of self-driving cars generally : software, hardware, behavior in a real environment, etc]

5.2 Natural Language and Robots, generally

5.3 Semantic Representations of NL for verification

Modal logics, specifically those dealing with time like LTL, CTL, STL, ..., have been used extensively in the specification and verification of properties of robotics systems, including autonomous vehicles [cite]

With verification being a core motivation of our work, we take for granted that these different logics have many manifestations in different systems. However, we hope that by choosing a domain with a lot of attention, that our system can be generalized in many possible directions :

- other logics
- other parsing formalisms (perhaps dependency for wide-coverage)
- other syntax -> semantic formalisms
- other robotics domains

5.4 Foundation Models

6 Work

6.1 GF Grammar

7 TODO

7.1 Grammar modulo wordnet

7.2 LTL in Agda

Along with colleagues from Singapore Management University, we have begun an Agda implementation [22] of LTL which will serve as the semantic space for our parsed utterances. Our method, uses a deep embedding, as opposed to the shallow embedding in [8], although the temporal encoding of paths as streams was directly adapted from this paper.

This implementation will hopefully allow us to prove decidability of LTL in a relatively straightforward manner. Other than the assurance that our implementation is correct, we hope this will allow us to feed the formula into some SAT or SMT solver so-as to actually allow verification of the behavior of a vehicle with respect to an utterance.

[TODO : Help from Matthew?]

7.3 AST -> Agda

7.4 ML training/verification stuff

Help from Marco, Nathalia if interested?

8 Publications Description

Realizing that the structure of the paper is ameanable to large changes, I'm posting a summary of relevant publications here.

8.1 Statistical (pre-trained) Language Models

The first set of publ

- In [31] [under review], the authors show how, using a *synchronous context-free grammar* (SCFG) to define a minified CNL with a parallel and dually parsible semantic form, that one can use a large pre-trained language model as a front-end to filter a much wider syntax into the CNL. I postulate GF's expressivity is more expressive than the SCFG,

at least based off a tertiary reading in the index, and therefore if we carved out a subset of commands to cohere with our LTL (and maybe some other temporal or even spatial-temporal logics in the future), our model would be amenable to a similar "out-of-the box" semantic parser that could actually be used for verification. This paper borrows the idea of "semantic parsing as paraphrasing" from [2]

- In [29], the authors advocate for getting rid of parsers alltogether, although this naively takes for granted large public data-sets, none of which exist for an autonomous vehicle and temporal logic formalism
- [13] [under review] claims that Bert is robust, analyzing claims of four papers, including the one which uses a wordnet attack

8.2 NL to TL

Here we show mainly relevant research for NL to LTL.

The applications of LTL in machine learning are vast, and the scope of our specific application is still unclear, but nevertheless, we give a literature review of methods and applications relevant for our work.

- This paper [10] from 2009 uses a categorial grammar approach, but more or less can serve as an idea template for us, also nice pictures with grammar rules and formulas
- Also, a highly relevant template combines Natural Language, LTL, with the idea of having a verifiable pipeline [19]

  > The production of an on- tology of common actions and the type of formulas that they produce—for example, safety conditions, adding goals, constraining the initial state—in their negated and positive forms would be a step toward a more general solution to the problem of mapping natural language to LTL. Previous work has relied heavily on grammar formalisms to ease... [19]

- LTL formulas can be transformed into automata which can then be used as reward functions for reinforcement learners, as in [6]
- The following is one of the more relevant quotes from a paper reviewing the whole space of English to LTL translations

  > Overall, the typical approach followed by these studies can be summarized as follows: given an input English utterance, preprocess it to extract syntactical information, which may include part of speech tagging, dependency parsing, semantic role labelling, and so on. Then, enrich the input with these pieces of information. Finally, run an attribute grammar-based parser, or rely on some hand-made rules, to derive a translation into a target logical format. A notable exception is the work of [89], where a fully-supervised learning setting is considered. [5]

- Translating between English and STL can be done via a large language model [14] [under review], but the domain specificity of the problems are still significant enough to suggest that it will be years before an automated semantic parser is available, if it is even possible.
- Could ask Lapata in Edinburgh, whose work [9] is relevant and well-cited (although they use an encoder-decoder method)
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-
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8.3 Tellex

Stephanie Tellex has written extensively about natural language inputs and interfaces with robots. Although she has not specifically written about autonomous vehicles, the domains have

enough intersection to warrant careful consideration of much of her work, especially the recent stuff.

- Grounding with an intermediate symbolic state, no LTL, but possibly relevant for paper generally. She also cites [20], a seminal paper in this area

  > Instruction following is a supervised learning problem where the agent must predict a trajectory that would satisfy an input natural language command. [11]

- The review paper [23] making recommendations has a section on robustness, but this is mostly for the sake of allowing sharing of interfaces and efficacy, no mention of verification (which is what we're primarily after)
- They design a NL -> LTL for drones that are grounded to actual landmarks [3]
- The group builds a trained pipeline that uses an object oriented template-instance methodology to generalize to different ontological categories in [15] [under review]
- In [25] build learn a semantic parser from NL to LTL (so that the language is grounded) where they collect executions of the LTL formulas in different environments using a weakly-supervised training method with reinforcement learning Part if the paper has to do with the execution of the command being dependent on the path taken by the robot executing the command, not just meeting the goal requirements, thereby giving a complexity bonus in comparison to previous work. She also evaluates the model on the [20] data set

8.4 Robot Motion Planning

Without getting to into the weeds, for the actual planning and control of the robot should, at least hypothetically, be at least somewhat

> Robot motion planning and control is the problem of automatic construction of robot control strategies from task specifications given in high-level, human-like language. The challenge in this area is the development of computationally efficient frameworks allowing for systematic, provably correct, control design accommodating both the robot constraints and the complexity of the environment, while at the same time allowing for expressive task specifications. [1]

- For instance, in [26] the authors indicate how to actually ground basic propositions from the language to paths in a space, while our model, outputting formulas un-grounded base predicates, is merely concerned with the logical structure.
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- In [4], the authors borrow the English to LTL pipeline from the aforementioned [19], and synthesize grounded controllers

There is a group at MIT (Kuo, Katz, Barbu, ..) doing seemingly similar things to Tellex's group.

- In [17], the authors do the most general end-to-end task without intermediary states, namely, map natural language commands to navigation and manipulation tasks. While this "cutting out the middle man" mentality may be an idealistic long-term vision, it makes the system much too much of a black box - for the fine-tuned verification conditions we desire to express and impose via the intermediate symbolic representations, the intermediate states, we imagine give us a more explainable, predictable, and regulatable system
- More similar to Tellex et al's approach [25], [34] seek to train a model via images in a simulated world. Their work also uses a SCFG (to generate semantically inadequate sentences with corresponding LTL formulas) from which they can direct machines to follow the instructions, and then have users describe the instructions in more natural form.
- One of the

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