On the syntax and semantics of voice assistants in autonomous vehicles

Warrick Macmillan

6^{th} May 2022

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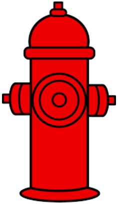

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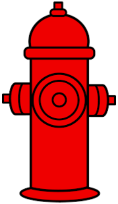

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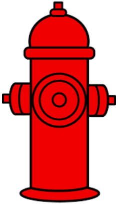

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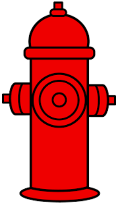

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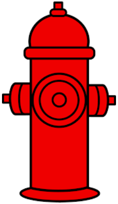

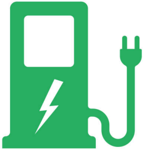

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"Go into the other lane"

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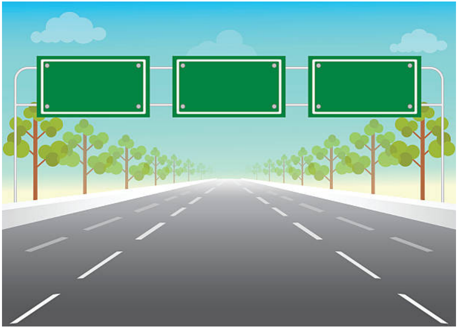

Ambiguities (cont.)

"Drive to the person with the dog"

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Simplified Autonomous Vehicle

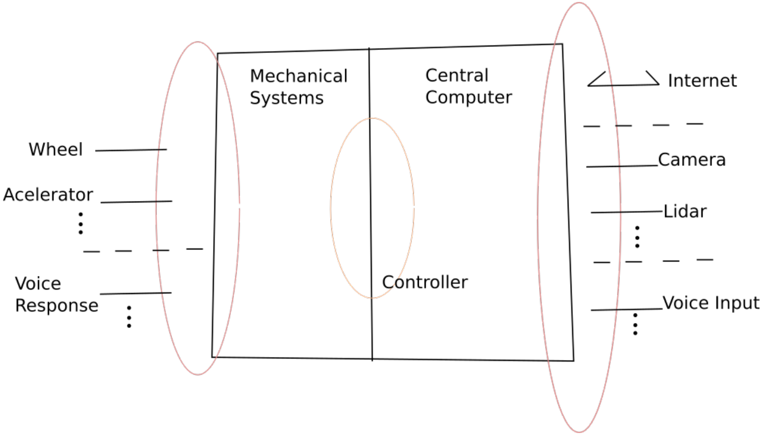

Figure: Self-driving car

Path

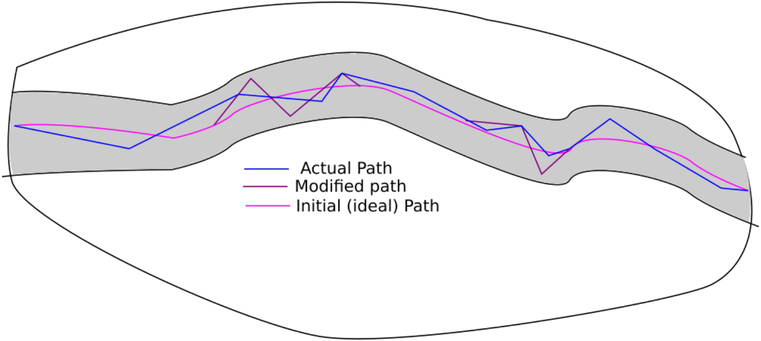

Figure: Initial, modified, and actual paths/routes

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$\forall u \in \text{Utt}.\ \exists r \in \text{Routes}$ such that $\forall r' \in \text{Routes}.\ d(u,r) \leq d(u,r')$

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- physical objects in the case of paths in Euclidean space

Verification Spectrum

Single Example	Set of Examples	Single Property	Metaproperty

Verifiability $\longrightarrow$

Unit Testing	Property-based Testing	Model Checking	ITP

$\xrightarrow{FP}$ $\longrightarrow$

Main Idea

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- Ensure maps between big-components are functorial with respect to small-component composition
- Verification of system is can similarly be broken into sub-verifications

More Specifically

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1. Functional Programming Languages : GF (Grammatical Framework), Haskell, Agda
2. Natural Language Processing : Semantic Parsing, Controlled Natural Languages
3. Tools : Grammars and logical implementations for motion planning and verification

Ideal Pipeline

$$
\begin{aligned}
\text{Utterance} & \xrightarrow{Speech\ Recognizer} \text{String} \\
& \xrightarrow{Canonicalization_{LLM}} \text{String} \\
& \xrightarrow{Parsing_{GF}} \text{Abstract Syntax Tree (NL)} \\
& \xrightarrow{[\![-]\!]_{Haskell}} \text{Abstract Syntax Tree (LTL)} \\
& \xrightarrow{\vDash_{Agda}} \text{Verifiable Path}
\end{aligned} \tag{1}
$$

Grammatical Framework

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- Separation of abstract (semantic and syntactic) and concrete (syntactic and morphological) considerations

Abstract Syntax

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Main Idea

By adding record types and natural number types to concrete categories we gain expressiveness

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```
([(["Go"],5527),(["be"],5300),(["turn"],4154),(["Turn"],4154)],["VB"])
([(["left"],228),(["came"],59),(["made"],47),(["started"],44)],["VBD"])
([(["going"],1684),(["facing"],939),(["moving"],849),(["passing"],617)],["VBG"])
([(["left"],1733),(["parked"],616),(["painted"],307),(["fenced"],263)],["VBN"])
([(["are"],3554),(["'re"],1185),(["reach"],1100),(["get"],770)],["VBP"])
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```

n-grams : the 9-gram “so you are moving with the flow of traffic” occurs 311

Ontological Categories

```
cat
  PosCommand    ; -- go to the store
  Place         ; -- the store
  Time          ; -- in 5 minutes
  Action        ; -- drive
  Way           ; -- to
  How           ; -- quickly
  Where         ; -- left
  AdvPh         ; -- to the store
  UndetObj      ; -- store
  Determ        ; -- the
  Object        ; -- the store
  Number        ; -- a
  Conjunct      ; -- and
  Condition     ; -- there is a museum
  Descript      ; -- big
```

GF Functions

```
fun
  -- Explicit Temporality
  DoTil      : Action -> Time -> PosCommand ; go in one minute

  -- Modified action
  ModAction : Action -> AdvPh -> Action ; -- go to the store

  -- Adverbial Phrases
  MkAdvPh     : Way   -> Object -> AdvPh ; -- to the store

  -- Noun Phrases
  WhichObject : Determ -> UndetObj -> Object ; -- the red dog

  -- Modified Noun
  ModObj : Descript -> UndetObj -> UndetObj ; -- black dog
```

Base Ingredients

These represent the tree leaves to be grounded!

```
fun
  Quickly : How      ;
  Left    : Where    ;
  To      : Way      ;
  After   : Way      ;
  Store   : UndetObj ;
  Traffic : UndetObj ;
  London  : Place    ;
  Drive   : Action   ;
  Turn    : Action   ;
  Big     : Descript ;
  A       : Determ   ;
```

go to the store, turn left and stop at the woman with the dog. go to the bridge. finish.

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p " go to the store , turn left  and stop at the woman with the dog . go to the bridge . Finish ." | tt
* ConsCommands
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        * CompoundCommand
            * And
              ConsPosCommand
                * SimpleCom
                    * ModAction
                        * Go
                          MkAdvPh
                            * To
                              WhichObject
                                * The
                                  Store
                  BasePosCommand
                    * SimpleCom
                        * ModAction
                            * Turn
                              WherePhrase
                                * Left
                      SimpleCom
                        * ModAction
                             Stop
                             MkAdvPh
                                * At
                                  WhichObject
                                    * The
                                      PhraseModObj
                                        * Woman
                                          MkAdjPh
                                            * With
                                              WhichObject
                                                * The
                                                  Dog
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Need a temporal until operator, U, to construct a semantically justifiable interpretation

Haskell LTL

go to the store, turn left and stop at the woman with the dog. go to the bridge. finish.

```
F (Meet
    (Atom "the_store")
    (F (Meet
        (Atom "turn_left")
        (F (Meet
             (Atom "the_woman_with_the_dog")
             (F (Meet
                  (Atom "the_bridge")
                  (G (Atom "FINISHED"))))))))
```

Haskell Semantics

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semantics :: GListCommands -> Phi
semantics x =
  let (GListCommands ((GOneCommand y) : _)) = normalizeList x
  in case y of
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normalizeList ::  GListCommands -> GListCommands
  where
    normalizeNestedLists :: GListCommands -> GListPosCommand
      where
        normalizeListPosCommand :: GListPosCommand -> GListPosCommand
          where
            unSentence :: [GCommands] -> [GPosCommand]
            flattenSublist :: GPosCommand -> [GPosCommand]
            where
              getListPosCommands :: GListPosCommand -> [GPosCommand]
```

Linear Temporal Logic

- Modal logic (temporal modality)
- Allows one to reason about sequential actions
- Verification for robotics systems
- Objective in reinforcement learning
- Other temporal logics (Signal TL, Computation Tree Logic, ...)
- Decidable

Complexity (and expressivity)

Propositional Logic < Temporal Logic $<_{undecidable}$ First Order Logic

Temporal Operators

- $X\phi$: in the next state, phi holds
- $\diamond\phi$: exists a future state such that ϕ holds $(F\phi)$
- $\Box\phi$: ϕ holds for every future state $(G\phi)$

```
data ϕ : Set where
  atom  : Atom → ϕ
  ⊥ ⊤   : ϕ
  ¬_    : ϕ → ϕ
  _∨_ _∧_ _⇒_ : ϕ → ϕ → ϕ
  X F G : ϕ → ϕ
  _U_ _W_ _R_ : ϕ → ϕ → ϕ
```

```
record M (Atom : Set) : Set1 where
  field
    State : Set
    _↪_ : rel State
    relSteps : relAlwaysSteps _↪_
    L : State → Atom → Set
    -- L'' : Decidable L'
```

```
alwaysSteps : (s : ℕ → State) → Set
alwaysSteps s = ∀ i → s i ↪ s (suc i)

record Path : Set where
  field
    infSeq : ℕ → State
    isTransitional : alwaysSteps infSeq

open Path

headPath : Path → State
headPath p = p .infSeq 0

tailPath : Path → Path
tailPath p .infSeq x = p .infSeq (suc x)
tailPath p .isTransitional i = p .isTransitional (suc i)

-- path-i == drop
path-i : ℕ → Path → Path
path-i n = nTimes n tailPath
```

mutual

$$\text{future} : \text{Path} \to \phi \to \text{Set}$$
$$\text{future}\ \pi\ \psi = \Sigma[\ i \in N\ ]\ (\text{path-i}\ i\ \pi) \vDash \psi$$

$$\text{global} : \text{Path} \to \phi \to \text{Set}$$
$$\text{global}\ \pi\ \psi = \forall\ i \to (\text{path-i}\ i\ \pi) \vDash \psi$$

$$\text{justUpTil} : N \to \text{Path} \to \phi \to \text{Set}$$
$$\text{justUpTil}\ i\ \pi\ \psi = \forall\ (j : N) \to j <'\ i \to (\text{path-i}\ j\ \pi) \vDash \psi$$

$$\text{upTil} : N \to \text{Path} \to \phi \to \text{Set}$$
$$\text{upTil}\ i\ \pi\ \psi = \forall\ (j : N) \to j \leq'\ i \to (\text{path-i}\ j\ \pi) \vDash \psi$$

$$\text{justUntil} : \text{Path} \to \phi \to \phi \to \text{Set}$$
$$\text{justUntil}\ \pi\ \psi\ \psi\ = \Sigma[\ i \in N\ ]\ (\text{path-i}\ i\ \pi) \vDash \psi\ \times \text{justUpTil}\ i\ \pi\ \psi$$

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```
_⊨_ : Path → ϕ → Set
π ⊨ ⊥         = ⊥'
π ⊨ T         = T'
π ⊨ atom p = L (headPath π ) p
π ⊨ (¬ ψ)   = ¬' (π ⊨ ψ)
π ⊨ (ψ ∨ ψ ) = (π ⊨ ψ)   (π ⊨ ψ )
π ⊨ (ψ ∧ ψ ) = (π ⊨ ψ) × (π ⊨ ψ )
π ⊨ (ψ ⇒ ψ ) = (π ⊨ ψ) → (π ⊨ ψ )
π ⊨ X ψ       = tailPath π ⊨ ψ
π ⊨ F ψ       = future π ψ
π ⊨ G ψ       = global π ψ
π ⊨ (ψ U ψ ) = justUntil π ψ ψ
π ⊨ (ψ W ψ ) = justUntil π ψ ψ    global π ψ
π ⊨ (ψ R ψ ) = until π ψ  ψ   global π ψ

_,,_⊨_ : (M : M  Atom) → (s : M .M.State) → ϕ → Set
M ,, s ⊨ ϕ = ∀ (π : Path) → headPath π   s → π ⊨ ϕ
```

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- Formality and formalizability
- Verifiability and validity

Future

- Expand parser itself

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- More expressive semantics

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- Better data set?

Where does ML come in?

Language Models

- Foundation models - future of NLP?

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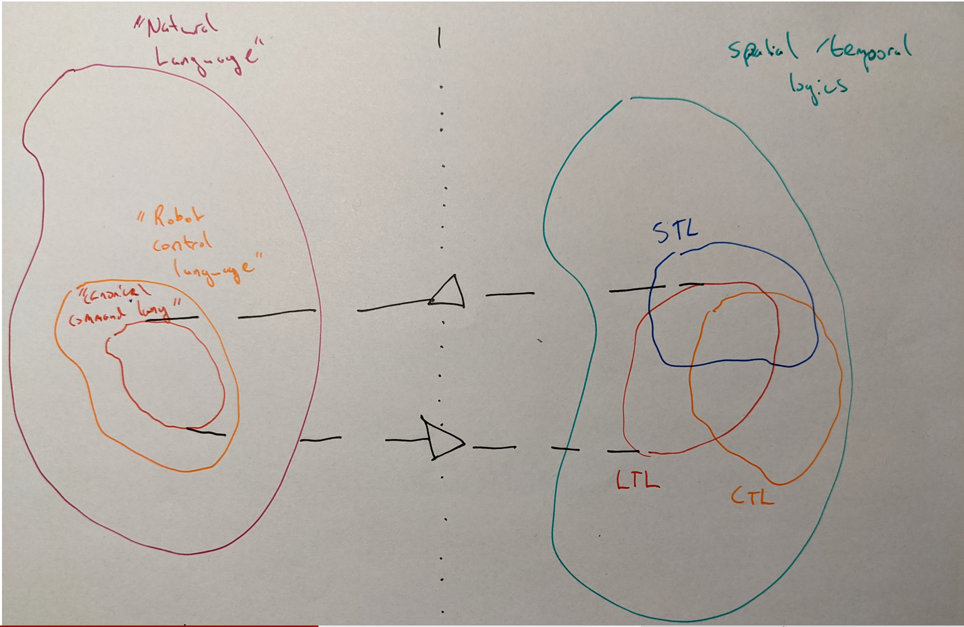
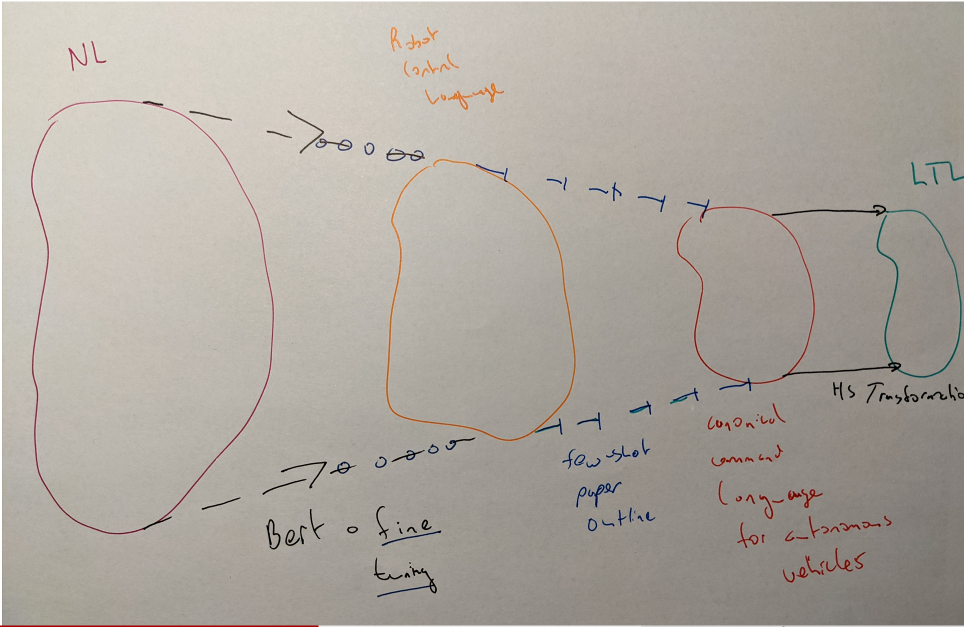
Light-bulb

Integrate their technique and code with our parser and dataset


"Natural Language"
"Robot control language"
"Canonical command lang"
Spatial / temporal logics
STL
LTL
CTL


NL
Robot
Control
Language
LTL
Bert o fine
tuning
few shot
paper
outline
canonical
command
language
for autonomous
vehicles

Acknowledgments

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