Developing Formal Correctness Properties from Natural Language Requirements

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Agenda

- Problem/Approach
- Relevance to NASA
- Potential Applications
- Accomplishments and/or Tech Transfer Potential
- Next steps
Problem/Approach

- Goal - transform natural language specifications into formal notation. Specifically, automate generation of Linear Temporal Logic (LTL) correctness properties from natural language temporal specifications.

- Why?
  - Model-based techniques becoming more widely accepted
  - Analytical verification techniques (e.g., model checking, theorem proving) significantly more effective at detecting types of spec. design errors (e.g., race conditions, deadlock) than manual inspection
  - Many requirements still written in natural language
    - High learning curve for specification languages, associated tools
    - Increased schedule and budget pressure on projects reduce training opportunities for engineers
  - Formulation of correctness properties for system models can be a difficult problem
Problem/Approach (cont’d)

- Develop more accurate classifiers to discriminate between temporal, non-temporal natural language requirements
  - Extend results of recently completed CI, reported in ISSRE2005¹
  - Improve probability of detection, reduce false positive rate
- Use pattern matching/natural language processing techniques to map identified natural language temporal requirements to LTL patterns
  - Correctness properties can often be specified as LTL expressions
- Extract semantic information to populate LTL pattern
  - Existing techniques (e.g., “-f” option for SPIN, LTL2BA²) can transform LTL expression into a “never” clause for model checkers (e.g., SPIN)

Problem/Approach (cont’d)

Schedule of Activities and Deliverables

- **Year 1**
  - Initial (manual) identification of temporal requirements within requirements documents of collaborating projects.
    - These requirements will be used as training sets for the classifiers and transformation tools developed for this task.
    - On-going throughout first year as additional collaborating projects contribute requirements
  - High-performance specification classifiers (temporal vs. non-temporal requirements)
  - Initial specification and design for tool to transform natural language temporal requirements to LTL expressions
  - End of first year report

- **Year 2**
  - Final specification and design for tool to transform natural language temporal requirements to LTL expressions; initial tool implementation.
  - Final toolset for transforming natural language temporal requirements into LTL expressions
  - Final Report
Relevance to NASA

- Simplify development of formal correctness properties
- More widespread use of model-based specification, design techniques

Rightarrow

- Earlier identification of defects
- Reduce residual defect content for space mission software systems
Potential Applications

- Model-based assurance techniques can
  - Find defects earlier in the development process
  - Find types of defects that cannot easily be found by test (e.g., race conditions, deadlocks, lack of progress cycles/starvation)

- Correctness properties
  - Manual specification of correctness properties can be difficult
  - Goal: Automated/assisted transformation of correctness properties written in natural language will simplify application of model-based techniques, encourage greater use

- More widespread use of model-based techniques will result in more reliable flight software.
Accomplishments and/or Tech Transfer Potential

- New task, work just starting
- Gathering requirements from collaborating projects – projected data availability high
  - Requirements for one project already in hand
  - Working with additional on-going projects to collect requirements for analysis
- Acquiring relevant classification, natural language processing tools. Several tools already in hand:
  - Link Grammar natural language parser
  - TnT parts-of-speech tagger
  - Weka
  - SPIN
- Projected Technology Transfer Level:
  - Year 1 (by June 07): 3 (“Experimental demonstration of critical function &/or proof of concept”)
  - Year 2 (by June 08): 4 (“Validation in a lab environment”) on collaborating flight projects
Next steps

Focus areas for next year

- Develop High Performance Classifiers
  - Improve ability to discriminate between temporal, non-temporal requirements
    - Try more classifiers – only a subset of classifiers in WEKA has been applied in previous work
    - Add more structural information to requirements being classified (e.g., parse tree information – part of speech, level in tree)
    - “Bagging” – apply more than one classifier, develop meta-classifier in which individual components are weighted according to how well they perform (e.g., pd, pf)
    - Direct pattern matching – use natural language parsing/transformation techniques to match structure of requirement to LTL pattern

- Map Temporal Requirements Structure to LTL Patterns
- Populate LTL patterns with semantic information
  - Work by Jane Malin, JSC, et al. (“Reconciler”) may be applicable
Machine Learning/Natural Language Processing (cont’d)

- Developing input to classifiers
  - Apply TnT POS tagger to requirement text
  - Form list of tags – n’th list element corresponds to n’th word in requirements text
  - Map each word in requirement to unique numerical ID
  - Map each POS tag to unique numerical ID
  - Concatenate requirements text word list, POS tag list
    - Use only first 200 elements of word list, POS tag list
  - Apply supervised discretization¹
    - Many classifiers require discrete data input
- Created training data sets (252 temporal requirements, 252 nontemporal requirements) that included the attributes accounting for the first 60%, 80%, and 90% of the classification merit
- Other input representations yielded poorer classifiers

Discriminating Between Requirement Types (cont’d)

Machine Learning/Natural Language Processing (cont’d)

- Five well-performing classifiers
  - AODE\(^1\)
  - RBF Network\(^2\) boosted with AdaBoostM1\(^3\)
  - Lazy Bayesian Rules (LBR)\(^4\)
  - NNGE\(^4, 5\)
  - NNGE boosted with AdaBoostM1\(^1\)

- Classifiers evaluated according to four criteria:
  - \(pd\) (probability of detection) - \(a/(a+b)\)
  - \(pf\) (probability of false detection, or “false positives”) - \(c/(c+d)\)
  - \(accuracy\) - \(c/(a+c)\)
  - \(precision\) - \( (a+d)/(a+b+c+d)\)

<table>
<thead>
<tr>
<th>Detected as temporal</th>
<th>Detected as nontemporal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>(b)</td>
</tr>
<tr>
<td>(c)</td>
<td>(d)</td>
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Return to Approach
Discriminating Between Requirement Types (cont’d)

Classifier Performance: Requirements Text and POS Information

Classifier Performance – Requirements Text and POS Information

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Classifier Performance – Requirements Text Information Only

Classifier Performance – Requirements Text Only

Return to Approach

Previous Slide
Example

- Natural language requirement text
  - “Electrical interfaces passing through cable cutter separation devices shall be deadfaced prior to actuation of the device”

- Requirements text parsed with Link Grammar parser\(^1,2\)

\[
(S \ (NP \ (NP \ Electrical \ interfaces)) \\
(VP \ passing) \\
(PP \ through) \\
(NP \ cable \ cutter \ separation \ devices))) \\
(VP \ shall) \\
(VP \ be) \\
(VP \ deadfaced) \\
(PP \ prior \ to) \\
(NP \ (NP \ actuation)) \\
(PP \ of) \\
(NP \ the \ device))))))))
\]

**Example (cont’d)**

- Matching LTL Pattern (patterns developed at KSU CIS Dep’t\(^1\))

\[
\begin{align*}
S & \text{ precedes } P: \\
(*) \text{ Globally} & \quad !P \mathrel{W} S \\
(*) \text{ Before } R & \quad \langle\rangle R \to (!P \mathrel{U} (S \mathrel{I} R)) \\
(*) \text{ After } Q & \quad []!Q \mathrel{|} \langle\rangle (Q \mathrel{&} (!P \mathrel{W} S)) \\
(*) \text{ Between } Q \text{ and } R & \quad []((Q \mathrel{&} !R \mathrel{&} \langle\rangle R) \to (!P \mathrel{U} (S \mathrel{I} R))) \\
(*) \text{ After } Q \text{ until } R & \quad [](Q \mathrel{&} !R \to (!P \mathrel{W} (S \mathrel{I} R)))
\end{align*}
\]

Where “\(W\)” represents the “weak until operator” and “\(U\)” represents the “strong until operator”, which are related as shown below:

\[
p \mathrel{W} q = ([]p) \mathrel{|} (p \mathrel{U} q) = <>(!p) \to (p \mathrel{U} q) = p \mathrel{U} (q \mathrel{|} []p)
\]

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Example (cont’d)

- Extract semantic information
  - Event “P” represented by noun phrase “(NP (NP actuation) (PP of (NP the device)))”
  - Event “S” represented by clause “(S (NP (NP Electrical interfaces) (VP passing (PP through (NP cable cutter separation devices)))) (VP shall (VP be (VP deadfaced))))”.
  - Corresponding LTL specification
    - !cable_cut W deactivate_electrical_interface
    - Equivalent to: <>(cut_cable) -> (!cut_cable U deactivate_electrical_interface)
Linear Temporal Logic

- Linear Temporal Logic (LTL) is a way of reasoning about a system’s desired properties
  - p is invariantly true
  - eventually p becomes invariantly true
  - p always implies not q
  - p always implies eventually not q
- Interesting in model checking context because an LTL expression corresponds to an automaton that can become part of the model being checked
- Introduced by Amir Pneuli in late 1970s
- Based on “tense logics” developed in 1950s
Linear Temporal Logic (cont’d)

- LTL can specify both safety and liveness properties
- LTL is **propositional logic** plus following temporal operators:
  - $\square p$: always $p$
  - $\triangleright q$: eventually $q$
  - $p U q$: $p$ until $q$
Linear Temporal Logic (cont’d)

Common LTL Expressions

- [] p  
  always p  
  invariance

- <> p  
  eventually p  
  guarantee

- p -> <> q  
  p implies eventually q  
  response

- p->q U r  
  p implies q until r  
  precedence

- [] <> p  
  always eventually p  
  recurrence (progress)

- <> [] p  
  eventually always p  
  stability (non-progress)

- <> p -> <> q  
  eventually p implies eventually q  
  correlation
Linear Temporal Logic (cont’d)

- Common LTL Rules
  - ![p] ⇔ <>!p
  - !<>p ⇔ []!p
  - !(p W q) ⇔ (!q) U (!p ∧ !q)
  - !(p U q) ⇔ (!q) W (!p ∧ !q)
  - [] (p ∧ q) ⇔ []p ∧ []q
  - <> (p ∨ q) ⇔ <>p ∨ <>q
  - p U (q ∨ r) ⇔ (p U q) ∨ (p U r)
  - (p ∧ q) U r ⇔ (p U r) ∧ (q U r)
  - p W (q ∨ r) ⇔ (p W q) ∨ (p W r)
  - (p ∧ q) W r ⇔ (p W r) ∧ (q W r)
  - [] <> (p ∨ q) ⇔ []<>p ∨ []<>q
  - <> [] (p ∧ q) ⇔ <>[]p ∧ <>[]q
Linear Temporal Logic (cont’d)

- Relationship between never claims and LTL
  - Desired property can be expressed as an LTL formula.
    - Requirement: “The electrical interfaces between the probe and the orbiter shall be deadfaced prior to activation of the cable cutting device”
    - Corresponding LTL formula: “Not p until s”, written as “!p U s”
      - “p”: activation of cable cutting device
      - “s” deadfacing of electrical interfaces
  - LTL formula is then negated (the negated property should NEVER occur)
    - Example: “!(!p U s)”
Linear Temporal Logic (cont’d)

- Relationship between never claims and LTL (cont’d)
  - Negated formula can then automatically be converted to a never claim using one of the spin execution options
  - Example – produce never claim to see if property “not p until s” can be violated by a model
    - spin –f ‘(!p U s)’ [> text file]

```c
never {  /* !(!p U s) */
    accept_init:
    T0_init:
        if
            :: (! ((s))) -> goto T0_init
            :: (! ((s)) && (p)) -> goto accept_all
        fi;
    accept_all:
        skip
}
```

Return to Approach
Propositional Logic Operators

- **Unary**
  - !: negation

- **Binary**
  - &&: logical and
  - ||: logical or
  - ->: logical implication
  - <->: logical equivalence

Return to Linear Temporal Logic
Strong vs. Weak Until

- **Weak until** ($p \ W \ q$)
  - A state $s_i$ satisfies $p \ W \ q$ iff
    - $s_i$ satisfies $q$, or $s_i$ satisfies $p$ and $s_{i+1}$ satisfies ($p \ W \ q$)
    - Formally: $s_i \models p \ W \ q$ iff $s_i \models q \lor (s_i \models p \land s_{i+1} \models (p \ W \ q))$
  - Never actually requires $q$ to become true

- **Strong until** ($p \ U \ q$)
  - A state $s_i$ satisfies $p \ U \ q$ iff
    - For some value of $j$, $j \geq 1$, $s_j$ satisfies $q$, and for all values of $k$, $i \leq k < j$, $s_k$ satisfies $p$
    - Formally: $s_i \models p \ U \ q$ iff $\exists j,(j \geq i): s_j \models q \land \forall k,(i \leq k < j): s_k \models p$
    - Requires that $q$ eventually become true

[Return to Linear Temporal Logic]