A Study on Mitigating Hard Boundaries of Decision-Tree-based Uncertainty Estimates for AI Models

Pascal Gerber, Lisa Jöckel, Michael Kläs

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Model-agnostic Uncertainty Wrappers provide dependable uncertainty estimates

Motivation

- The outcomes of Data-Driven Models (DDMs) cannot be assumed to be always correct
  - The outcomes of DDMs are subject to uncertainty
- Different approaches exist to provide ‘inside-model’ or ‘outside-model’ uncertainty estimates
- An example of the latter is the concept of **model-agnostic Uncertainty Wrappers**
  - Uncertainty Wrappers enrich DDMs with a dependable uncertainty estimate

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Data-Driven Component Input (e.g., camera image)

Influence factors (e.g., rain sensor, sun angle, distance, GPS, …)

Confidence (e.g., 99.99%)

Uncertainty Wrapper for Pedestrian Detection

Existing Data-Driven Model (DDM): YOLOv3-based pedestrian detection

Outcome (e.g., bounding box for a pedestrian)

Dependable Uncertainty Estimate (e.g., < 4%)
Decision Trees can be used to obtain interpretable uncertainty estimates

**Motivation**

- **Uncertainty Wrappers** *cluster inputs with similar uncertainties* based on influence factors using Decision Trees
- **Benefit of Decision Trees:** uncertainty estimates are *easy to interpret*

- **Example:** \( x_1: \text{semantic\_visibility} = 0.3, \ldots, \text{distance} = 11.450 \Rightarrow \text{uncertainty estimate} = 16\% \)
Decision Trees may lead to undesired hard decision boundaries

**Problem Statement**

- Problem: The discrete approach of Decision Trees realizes **hard decision boundaries**
- For **continuous features**, these boundaries may be rather unintuitive

**Example evaluation:**

- $x_1: \text{semantic\_visibility} = 0.3, \ldots, \text{distance} = 11.450$  =>  uncertainty estimate = 16%
- $x_2: \text{semantic\_visibility} = 0.3, \ldots, \text{distance} = 11.451$  =>  uncertainty estimate = 43%
Goals to be met by the softening approaches

Solution search

- Approaches need to satisfy the following goals:
  - G1: Implement soft decision boundaries
  - G2: Interpretable uncertainty estimates
  - G3: Reasonable runtime complexity
  - G4: Reasonable uncertainty estimation performance

- Identified approaches:
  - Random Forests:
  - Fuzzy Decision Trees / Random Forests:
    In Proceedings of Int. Conf. on Fuzzy Systems, 1-8. IEEE.
  - Soft Decision Trees / Bagged Soft Decision Trees:
Softening is achieved by using membership functions

Solution approaches

- **Main concept**: A data point has a membership degree to the leaves
- **Uncertainty estimate** = Weighted sum of leaf uncertainties and membership values
- Key difference between the approaches is the type of membership function used
- Simplified example of a Fuzzy Decision Tree to determine an uncertainty estimate for an input $\mathbf{X}$:

\[ \text{uncertainty}(\mathbf{X}) = 0.0 \cdot 0.93 + 0.5 \cdot 0.38 + 0.25 \cdot 0.08 + 0.25 \cdot 0.24 + 0.0 \cdot 0.57 = 0.27 \]
Softening approaches evaluated on pedestrian detection use case and metrics

Evaluation

- Use case: **Pedestrian detection** on roads
- Study execution – **build datasets**:

![Diagram](image)

- Study execution – **evaluate softening approaches**:

![Diagram](image)
Results: Softening achieved, but decreased estimation performance

**Evaluation**

- Summary of the extent to which the approaches achieve our goals:

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<tbody>
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<td>Decision Trees (baseline)</td>
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<td>Random Forests</td>
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Softening is a trade-off decision dependent on the use case

Conclusion and future work

- A general recommendation for the use of a particular approach cannot be provided
- Rather, the selection of an approach has proved to be a trade-off decision

Based on the study results, we see two main directions for further work:

- Develop specific recommendations for choosing an approach for a concrete setting
- Modify approaches to address the observed uncertainty estimation performance limitations