NSF-CPS: Medium: Spatio-Temporal Logics for Analyzing and Querying Perception Systems

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Signal Temporal Logic (STL)

Signal Temporal Logic is a logic formalism for specifying linear-time properties of continuous, real-valued signals and is widely used in verification, testing and monitoring of Cyber-Physical Systems (CPS).

- Allows us to check at runtime whether an output trace of a CPS satisfies a safety property or specification.
- Provides a robustness metric to measure the degree to which a signal satisfies or violates a requirement expressed in STL.

One important application is the monitoring of vision-based perception systems. Autonomous vehicles, for example, heavily depend on the correctness of perception systems and any inaccuracies can lead to potentially catastrophic incidents. Existing metrics used in vision and object tracking are limited and so the utilization of formal specifications can greatly improve the evaluation of perception systems in order to guarantee safety in such scenarios.

Multimodal Distributional Metrics in Evaluation

We have proposed style and model sensitivity measures [4] that can be used to identify unique or out-of-distribution examples with applications to caption evaluation (Figure 1) and uncertainty quantification/outlier detection (Figure 2).

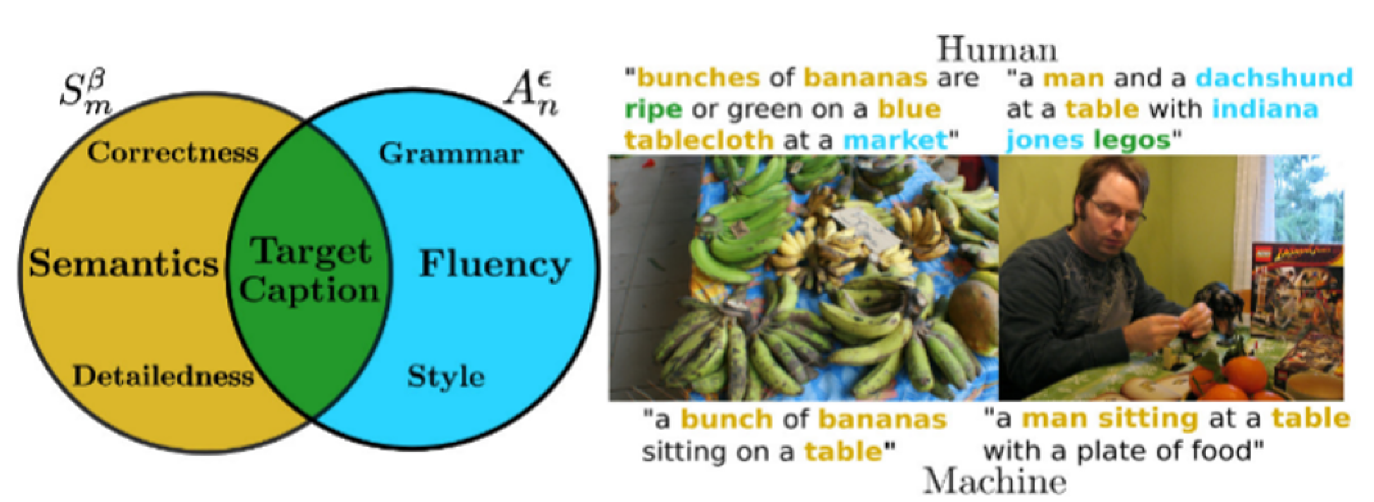


Figure 1

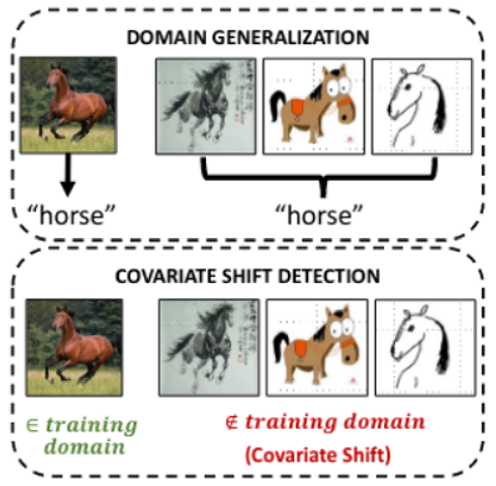


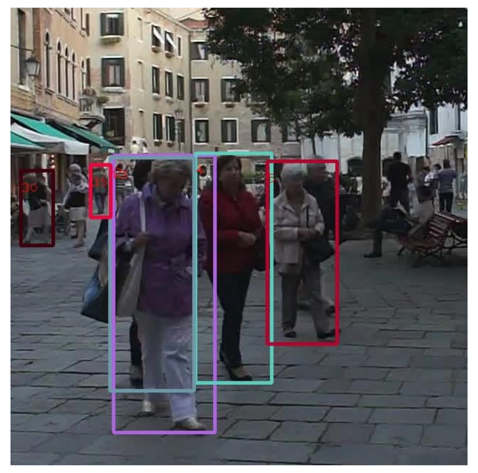
Figure 2

Spatio-Temporal Quality Logic (STQL)

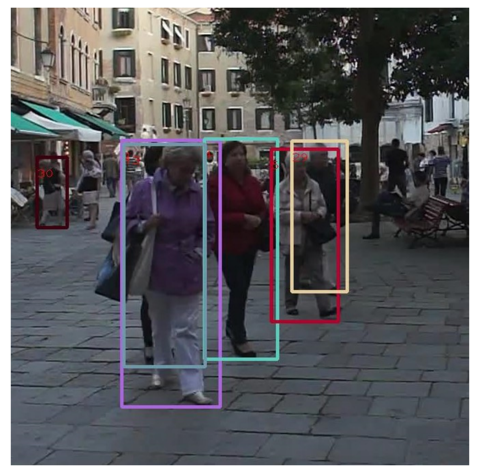
Spatio-Temporal Quality Logic (STQL) [5] is an extension of Timed Quality Temporal Logic (TQTL) [3, 1] that incorporates reasoning about high-level topological structures present in perception data, like bounding boxes, and set operations over these structures.

- Allows us to specify quantifiers over objects in a scene, and reference frames of data at different time instances.
- Can explicitly reason about attributes associated with objects, e.g., object type, confidence associated with detections, etc.
- Perform topological set operations over bounding boxes associated with each object.
- Compute and compare the area occupied by objects, relative positions of objects, and Euclidean distance between objects.

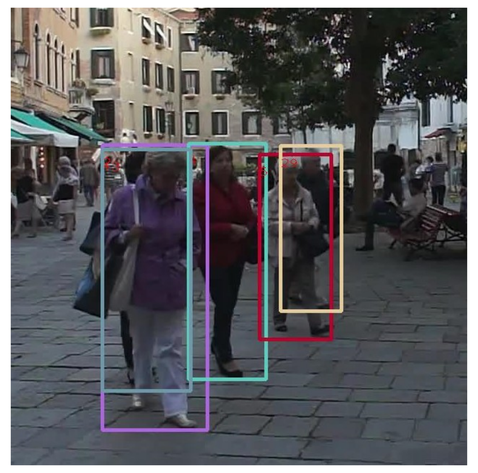
$$
\begin{aligned}
\varphi ::= \;& \exists\{id_1, id_2, \ldots\}@\varphi \mid \{x, f\}.\varphi \\
& \mid \top \mid \neg\varphi \mid \varphi \vee \varphi \mid \bigcirc \varphi \mid \ominus \varphi \mid \varphi\, \mathbf{U}\, \varphi \mid \varphi\, \mathbf{S}\, \varphi \\
& \mid \mathsf{C\_TIME} - x \sim t \mid \mathsf{C\_FRAME} - f \sim n \\
& \mid \mathsf{C}(id_i) = c \mid \mathsf{C}(id_i) = \mathsf{C}(id_i) \mid \mathsf{P}(id_i) \geq r \mid \mathsf{P}(id_i) \geq r \times \mathsf{P}(id_j) \\
& \mid \{id_i = id_j\} \mid \{id_i \neq id_j\} \mid \boxed{\exists}\, \Omega \mid \Pi \\
\Omega ::= \;& \varnothing \mid\mid \mathfrak{BB}(id_1) \mid \overline{\Omega} \mid \Omega \sqcup \Omega \\
\Pi ::= \;& \mathsf{Area}(\Omega) \geq r \mid \mathsf{Area}(\Omega) \geq r \times \mathsf{Area}(\Omega) \\
& \mid \mathsf{ED}(id_i, \mathrm{CRT}, id_j, \mathrm{CRT}) \geq r \mid \Theta \geq r \mid \Theta \geq r \times \Theta \\
\Theta ::= \;& \mathsf{Lat}(id_i, \mathrm{CRT}) \mid \mathsf{Lon}(id_i, \mathrm{CRT}) \\
\mathrm{CRT} ::= \;& \mathsf{LM} \mid \mathsf{RM} \mid \mathsf{TM} \mid \mathsf{BM} \mid \mathsf{CT}
\end{aligned}
$$



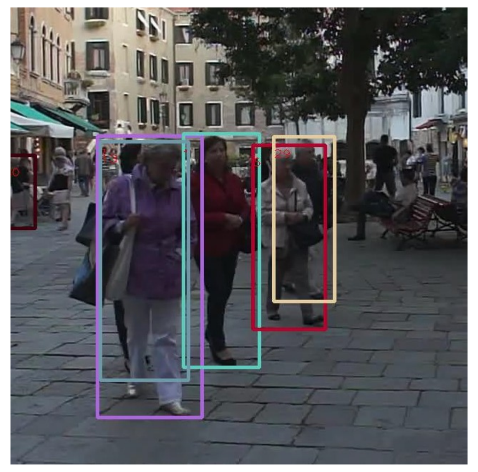
(a) Frame 122.



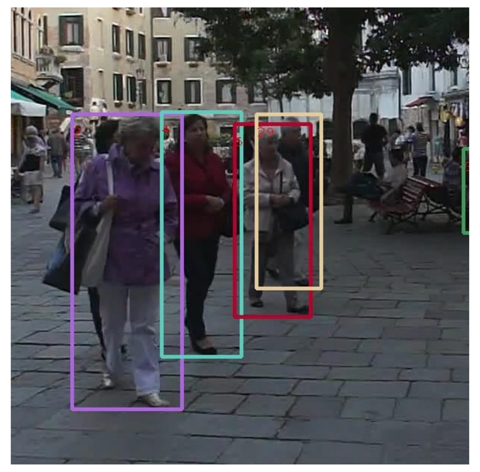
(b) Frame 123.



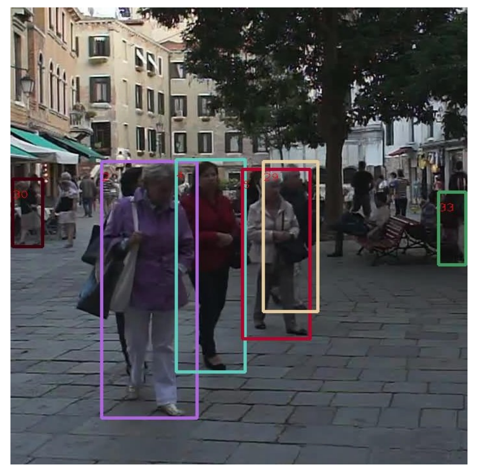
(c) Frame 124.



(d) Frame 125.



(e) Frame 126.



(f) Frame 127.

Figure 3. A snippet from the MOT dataset [6]. The bounding boxes around the pedestrians in the frame are being lost due to various reasons, including occlusions. STQL-based perception monitors, using the *PerceMon* tool [2] are able to detect these occlusions before it happens.

Improving Policy for Learning-based Agents Using Signal Temporal Logic

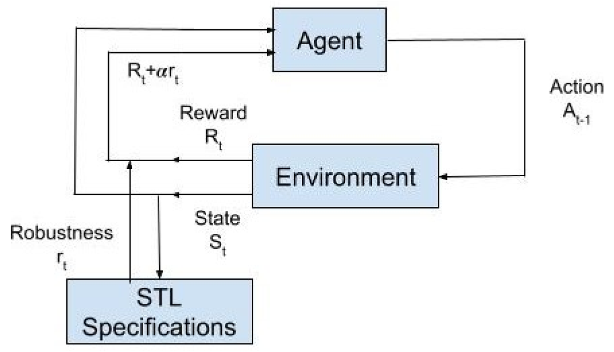


Figure 4. Reward shaping using the robustness of STL Specifications.

- We adopt Responsibility-Sensitive Safety (RSS) model;
- We use STL specifications for RSS modeling;
- To improve robustness of scenario specifications;
- To improve robustness as additional reward signal for RL;
- Online learning-based policy improvement using STL.

Future Work

To enable querying of databases with perception data for specific driving scenarios without the need for the highly manual process of creating ground truth annotations.

This framework sets the foundation for a requirements language between suppliers of perception components and automotive companies. The open source and publicly available software tools developed will assist with testing of perception systems.

References

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[3] Adel Dokhanchi, Heni Ben Amor, Jyotirmoy V. Deshmukh, and Georgios Fainekos. Evaluating Perception Systems for Autonomous Vehicles Using Quality Temporal Logic. In Christian Colombo and Martin Leucker, editors, *Runtime Verification*, Lecture Notes in Computer Science, pages 409–416. Springer International Publishing, 2018. ISBN 978-3-030-03769-7. doi:10.1007/978-3-030-03769-7_23.

[4] Joshua Feinglass and Yezhou Yang. Smurf: Semantic and linguistic understanding fusion for caption evaluation via typicality analysis. In *Proceedings of the 59th Annual Meeting of the Association for Computational Linguistics and the 11th International Joint Conference on Natural Language Processing (Volume 1: Long Papers)*, pages 2250–2260, 2021.

[5] Mohammad Hekmatnejad. *Formalizing Safety, Perception, and Mission Requirements for Testing and Planning in Autonomous Vehicles*. PhD thesis, Arizona State University, 2021.

[6] Anton Milan, Laura Leal-Taixe, Ian Reid, Stefan Roth, and Konrad Schindler. MOT16: A Benchmark for Multi-Object Tracking. *arXiv:1603.00831 [cs]*, May 2016. URL `http://arxiv.org/abs/1603.00831`.