12-8-2023

Experimental Validation of Uncertainty Quantification Methods for Robot Perception

Yifei Li
Washington University in St. Louis, liyifei@wustl.edu

Washington University in St. Louis
James McKelvey School of Engineering

Experimental Validation of Uncertainty Quantification Methods for Robot Perception

Yifei (Bruce) Li, Department of Electrical & Systems Engineering
Research Advisor: Professor Yiannis Kantaros

INTRODUCTION

Background

In real-world settings, from woking in manufacturing plants to self driving on highway, robots empowered by Machine Learning (ML) models are tasked with complex, dynamic tasks that demand high levels of precision and adaptability. The reliability of these systems hinges on the perception capabilities of ML model, making uncertainty quantification methods vital. Conformal prediction is a user-friendly paradigm for creating statistically rigorous uncertainty sets/intervals for the predictions of such models. [1] It ensures that robots can effectively assess and respond to varying conditions with safe and trustworthy actions, reducing the risk of errors and enhancing overall system performance.

Purpose

The purpose of this research project is to experimentally validate the effectiveness conformal prediction in object detection of a control algorithm on a ground robot platform.

PROBLEM STATEMENT

Given

- The physical environment distributed with objects.
- A robot and its planned navigation control scheme.

Find

- Make safe, trustworthy actions based on result of object detection and conformal prediction.

METHOD & PROCEDURE

1. Setup

- We will use the Turtlebot 3 Waffle Pi, a 2-wheel ROS based ground robot platform with build in camera, in the Gazebo simulated world.

2. Object Detection

- For the robot perception algorithm, we choose YOLOv7 object detection with pre-trained weights on the Microsoft COCO (Common Objects in Context) Dataset. [4]
- State-of-the-art performance in real-time object detection, capable of identify and classify multiple objects in complex environments with minimal latency and high precision.

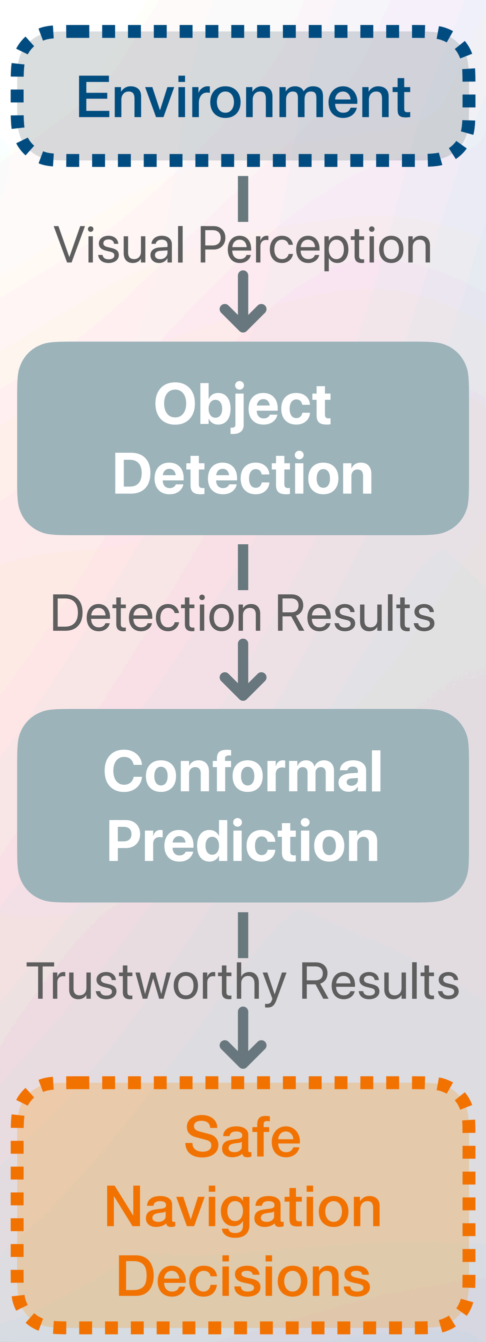


Fig. 1 a block diagram of the procedure of solving the problem

2. Object Detection (cont.)

- Common object detector assumes each bounding box contains one instance of object class.
- Assume two bounding boxes are over the same object if their intersection over union (IoU) is greater than 0.3.
- Resulting in multiple bounding boxes with each labeled with multiple class instances and scores.

Algorithm 1 Merge Detections

```
for each bbox_1 in detections do
    for each bbox_2 in detections do
        Compute intersection over union
        if iou > threshold then
            x_min ←min(bbox_1 → x_min, bbox_2 → x_min)
            x_max ←min(bbox_1 → x_max, bbox_2 → x_max)
            y_min ←min(bbox_1 → y_min, bbox_2 → y_min)
            y_max ←min(bbox_1 → y_max, bbox_2 → y_max)
            Append class, score of bbox_1 and bbox_2
        end if
    end for
end for
```

3. Conformal Prediction

Given each output (bounding box) of object detection that contain K classes.

$$\hat{f}(x) \in [0,1]^K$$

Find conformal score ($1 -$ score of true class):

$$s_i = 1 - \hat{f}\left(X_i\right)_{Y_i}$$

Construct empirical quantile $\hat{q} = \frac{\lceil (n+1)(1-\alpha) \rceil}{n}$-th element of $s_1, \ldots, s_n$ from calibration set

Make the inference to choose form set of classes:

$$\mathscr{C}\left(X_{test}\right) = \left\{y : \hat{f}\left(X_{test}\right)_y \geq 1 - \hat{q}\right\}$$

That is granted to satisfy [1]:

$$1 - \alpha \leq \mathbb{P}\left(Y_{test} \in \mathscr{C}\left(X_{test}\right)\right) \leq 1 - \alpha + \frac{1}{n+1}$$

```python
# 1: get conformal scores. n = calib_Y.shape[0]
cal_smx = model(calib_X).softmax(dim=1).numpy()
cal_scores = 1-cal_smx[np.arange(n),cal_labels]
# 2: get adjusted quantile
q_level = np.ceil((n+1)*(1-alpha))/n
qhat = np.quantile(cal_scores, q_level, method='higher')
val_smx = model(val_X).softmax(dim=1).numpy()
prediction_sets = val_smx >= (1-qhat) # 3: form prediction sets
```

Fig. 3 conformal prediction Python code [1]

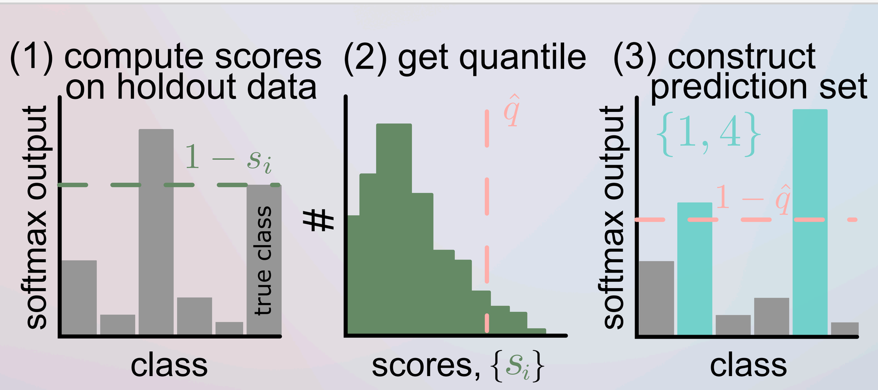
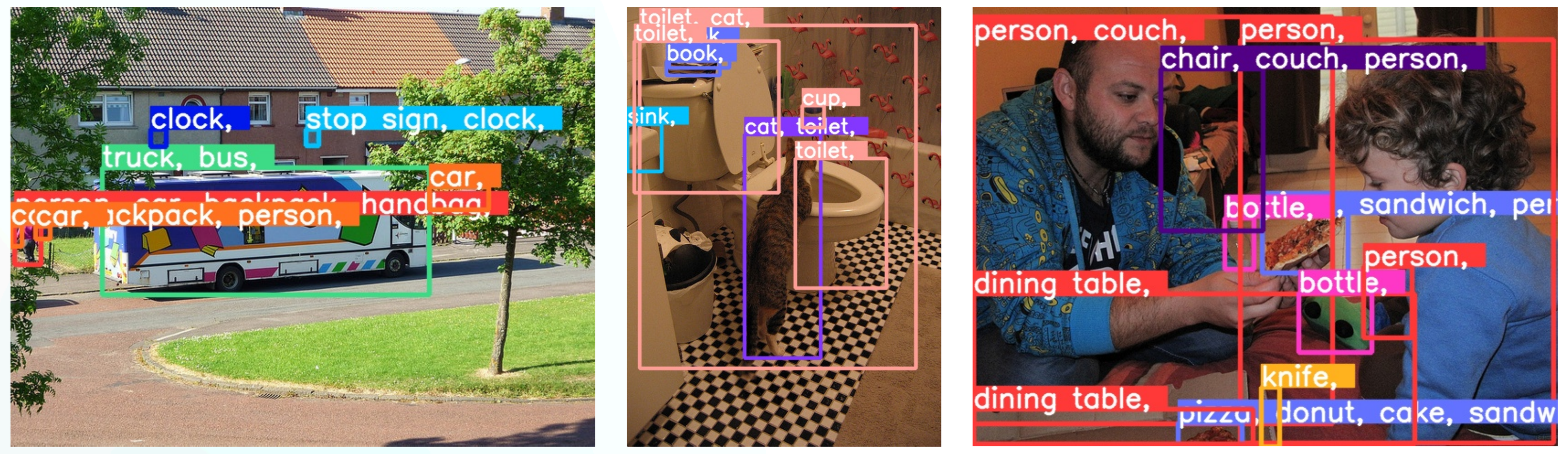


Fig. 2 illustration of conformal prediction [1]

RESULTS

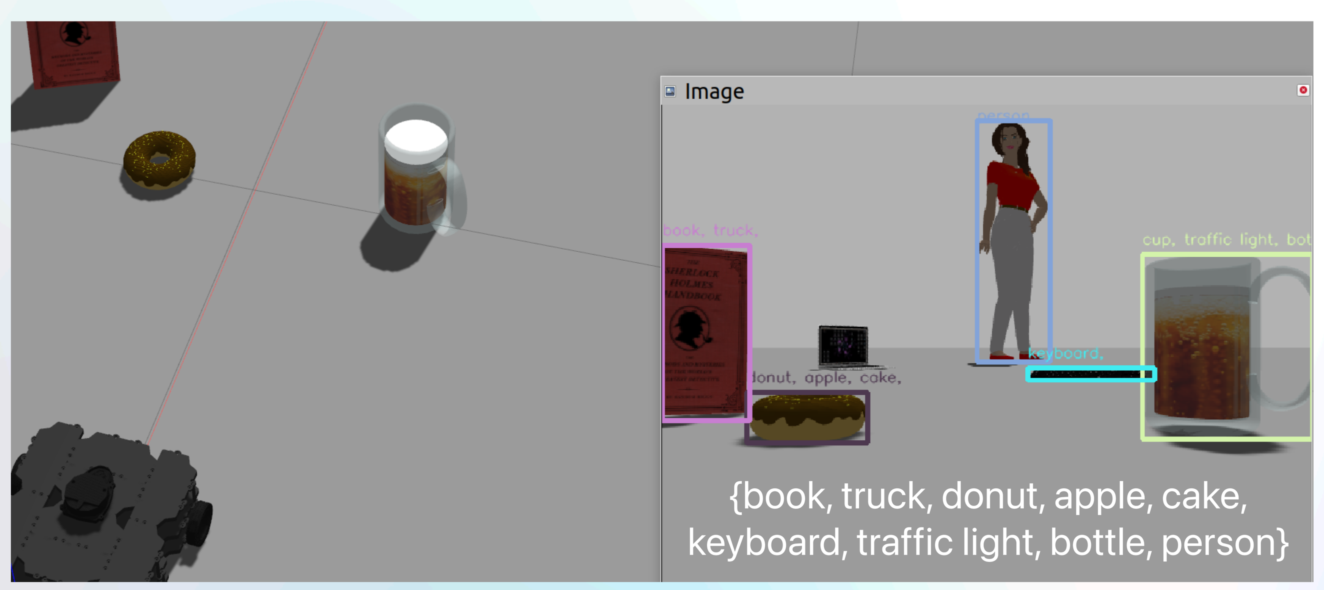
We first tested the object detection with conformal prediction with still images random selected COCO dataset:



{person, car, bus, truck, stop sign, backpack, handbag, clocks} {cat, cup, toilet, sink, book} {person, bottle, knife, sandwich, pizza, donut, cake, chair, couch, dining table}

Fig. 4,5,6 bounding boxes, labels of detected objects with conformal prediction in random selected COCO dataset images

During our test in Gazebo simulator, With lack of custom trained detection model, the algorithm performs sub-optimally in simulated world. Which highlights the fact that conformal prediction can provide statistically promising results when model predictions are inaccurate.



{book, truck, donut, apple, cake, keyboard, traffic light, bottle, person}

Fig. 7 portion of the test simulated world with random objects with camera detection view on the side

CONCLUSION & FUTURE DIRECTIONS

In this research project, we presented an experimental validation of uncertainty quantification for robot perception.

Our results demonstrated that the proposed approach was effective in generating detection results that contain the true label with high probability. [2]

By validating the effectiveness of the conformal prediction in a simulated setting with the specific model of robot, we can contribute to the development of more safe and trustworthy robotic controls.

Future directions could be: implement classification with Adaptive Prediction Sets[1]; train custom detection models; test the perception method and analyze it's performance in physical lab setting; and integrate with existing navigation algorithms.

REFERENCES

[1] A. N. Angelopoulos and S. Bates, A Gentle Introduction to Conformal Prediction and Distribution-Free Uncertainty Quantification. 2022.
[2] S. Li, S. Park, X. Ji, I. Lee, and O. Bastani, Towards PAC Multi-Object Detection and Tracking. 2022.
[3] L. Andéol, T. Fel, F. D. Grancey, and L. Mossina, Confident Object Detection via Conformal Prediction and Conformal Risk Control: an Application to Railway Signaling. 2023.
[4]C.-Y. Wang, A. Bochkovskiy, and H.-Y. M. Liao, "YOLOv7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors," 2023.