

# 3D-Object Perception Transformer (3PT)

## Supplementary Material

### 6. Supplementary Materials

The supplement provides additional details and videos organized.

- *Video versions of Fig. 6 for additional methods*
  - [3pt\\_vs\\_Freeze.mp4](#)
  - [3pt\\_vs\\_Foundationpose.mp4](#)
  - [3pt\\_vs\\_FRTPose.mp4](#)
- *Robotic Bin-Picking:*
  - Sec. 6.3
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- *AR Tracking:*
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- *DIMM Insertion:*
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- *BOP Leaderboards/Challenge Results:* Sec. 6.1
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#### 6.1. BOP Leaderboards / Challenge

3PT participated in the BOP-2025 Challenge (under the name IPT) and achieved the following results:

##### BOP-Classic-Core

- Model-based 2D detection of unseen objects. *First Place.*

##### BOP-H3

- Model-based 2D detection of unseen objects. *First Place.*
- Model-free 2D detection of unseen objects. *First Place.*
- Model-based 6D detection of unseen objects. *First Place.*

##### BOP-Industrial

- Model-based 2D detection of unseen objects. *First Place.*
- Model-based 2D detection of seen objects. *Second Place.*
- Model-based 6D detection of unseen objects. *First Place.*
- Model-based 6D detection of seen objects. *First Place.*

As of Nov. 14, 2025, 3PT leads 9 separate leaderboards on the BOP-Website [27]. For each entry we specify the difference between our approach and the previous best. Our approach often achieves double digit performance improvements and in some cases outperforms *seen* methods while being zero-shot.

##### BOP-Classic-Core

- Model-based 2D detection of unseen objects.  
#1 (+4.7 AP)

Table 4. Retraining our model on a MegaPose size-matched version of our dataset still outperforms the previous SoTA.

Method	Training Data	BOP-H3 AP	BOP-Classic AP	BOP-Industrial AP-mm
Prev. SoTA	–	46.4	60.6	68.3
3PT (Ours)	Ours Smaller	54.1	65.7	79.7
<b>3PT (Ours)</b>	<b>Ours Full</b>	<b>58.7</b>	<b>66.0</b>	<b>80.6</b>
Relative $\Delta$ (%)		+26.5	+8.9	+18.0

- Model-based 2D segmentation of unseen objects.  
#1 (+1.1 AP)
- Model-based 6D detection of unseen objects - RGB-Only.  
#1 (+8.3 AP)

##### BOP-H3

- Model-based 2D detection of unseen objects.  
#1 (+13.0 AP)
- Model-free 2D detection of unseen objects.  
#1 (+4.1 AP)
- Model-based 6D detection of unseen objects.  
#1 (+12.3 AP)

##### BOP-Industrial

- Model-based 2D detection of unseen objects.  
#1 (+17.5 AP)
- Model-based 2D detection of seen objects.  
#2 (−10.2 AP)
- Model-based 6D detection of unseen objects.  
#1 (+4.1 AP, +12.3 AP-mm)
- Model-based 6D detection of seen objects.  
#1 (+0.5 AP, +6.6 AP-mm)

#### 6.2. Dataset Size

We retrained 3PT-R and 3PT-D on a dataset comparable in CAD models (22K vs. 20K) but smaller in image volume (200K vs. 2M). Tab. 4 shows that training on the reduced dataset leads to only an average −1.9 AP performance drop across BOP-Classic, BOP-Industrial, and BOP-H3. Even at this scale, our 3PT achieves SoTA results. This is noteworthy as 3PT forgoes the extra generalization that competitors gain by using existing foundation models trained on massive datasets (*e.g.*, GroundingDINO [39], SAM [37]). See Fig. 7.

#### 6.3. Bin Picking

**Setup.** A UR10e 6-axis manipulator, equipped with a vacuum suction gripper, is used for emptying objects from a bin. Three overhead cameras, mounted at a distance of 2m, provide grayscale images. *Main Test:* The task involves emptying a bin containing 100 thin sheet-metal parts, each with dimensions of 140×140×1.5mm. The parts are ran-

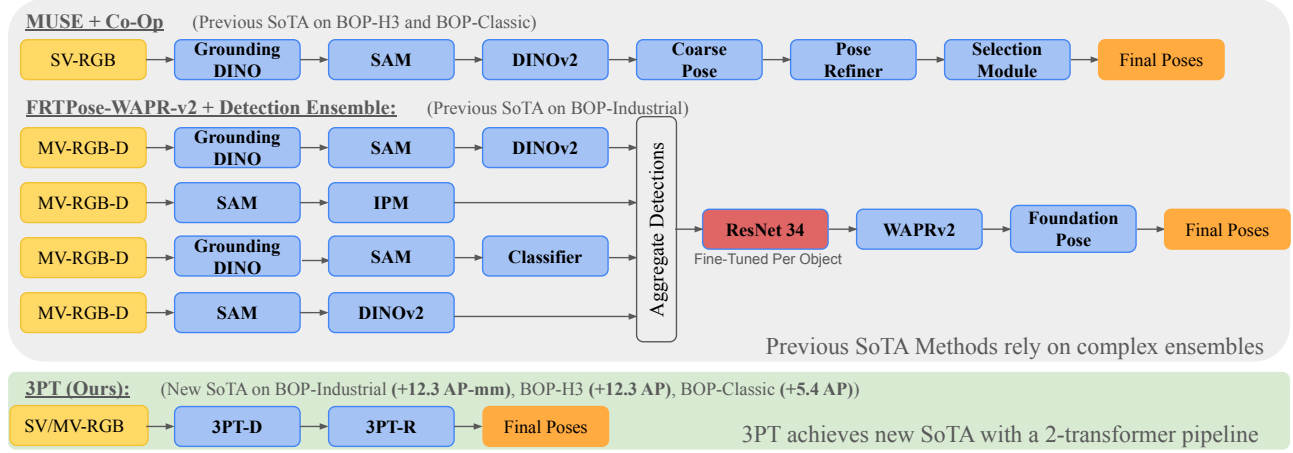


Figure 7. **3PT (bottom) simplifies the pipeline down to two models while outperforming prior SoTA.**

domly scattered in the bin to create a high-density, cluttered environment. *Stress Test:* We extend the task to contain 3 different object classes. 2 of them are very similar-looking brackets, differing only in number of holes and size.

**Challenges.** The successful execution of the bin-picking task depends critically on achieving highly accurate 6D pose estimation under challenging geometric and operational constraints. This is compounded by two main factors: long-range perception from the 2m camera height, and severe inter-part occlusion created by the dense, scattered stack of thin (1.5mm) sheet-metal objects. Even minor pose errors, on the order of a few millimeters or degrees, lead to vacuum pressure loss in the gripper or collisions with surrounding objects during extraction. These failures often result in the object being dropped outside the bin or unpredictably thrown outside the bin at high speeds.

We further stress-test the system’s ability to distinguish between brackets with subtle differences such as small changes in geometry (different holes) during the picking task.

**Method.** We start with an offline grasp planner, which pre-computes valid grasp poses relative to the object’s mesh origin. We then employ an online sense-plan-act strategy for every pick and place cycle. During the sense phase, 3PT generates pairs of 6D poses and scores for each detection. The plan phase then selects the detected object pose associated with the highest score and computes a collision-free grasp and extraction trajectory. The planned motion is executed in the act phase *without* any corrective force, move until suction, or visual servoing feedback. For placement, the objects are simply dropped at a predetermined location.

**Results.** In the main test, 3PT achieves a 100% bin clear rate, clearing 100/100 parts in the bin with zero failures. For

the stress test, it is able to correctly identify, pick, and sort all 3 part types, including similar-looking brackets.

#### 6.4. Application: Precision DIMM Insertion

**Setup.** We employ a KUKA KR6 6-axis industrial robotic arm equipped with a custom two-jaw parallel gripper to manipulate DIMM modules. The perception system consists of three RGB Basler Ace cameras mounted directly on the gripper, arranged 120 degrees apart. The robotic control loop is managed via proprietary software, while 3PT provides the underlying 6DoF pose estimation *for both* the DIMM modules and the target PCB.

**Challenges.** The task imposes strict accuracy requirements due to the tight mechanical tolerances of the DIMM and insertion slot. Grasping the DIMM requires a pose accuracy of approximately  $\pm 2\text{mm}$  from a distance of 30–40cm. The insertion phase is significantly more demanding: the DIMM slot clearance is merely 0.57mm, requiring a PCB pose estimation accuracy within  $\pm 0.285\text{mm}$  and  $\pm 2^\circ$ .

**Method.** The operation follows a coarse-to-fine visual servoing strategy. First, 3PT estimates the PCB pose from a distance of 70cm (where the entire board is visible) to establish a coarse global alignment. Next, the robot moves to the feeder tray to resolve the 6DoF pose of the incoming DIMM stick for grasping.

For the insertion phase, the strategy varies by slot location due to visibility constraints. For the central 8 slots, the robot hovers at close range to perform a high-precision refinement step immediately prior to each insertion. For the outer 8 slots, where gripper geometry occludes two cameras during the approach, we perform a single refinement step before picking the DIMMs and execute the insertion “blind” based on this cached pose estimate. Crucially, the insertion

trajectory relies exclusively on these visual pose estimates without force guidance; force feedback is employed solely for the final locking mechanism (clicking the DIMM into place).

**Results.** We evaluated the system by filling a complete server tray (16 slots) over 6 independent trials, achieving 96/96 successful insertions. To test robustness, both the DIMM feeder and the receiving PCB were arbitrarily repositioned between runs. A video demonstrating a full sequence of 16 successful insertions is included in the supplementary material.

### 6.5. Additional Runtime Discussion

Table 5 presents a detailed runtime breakdown across the BOP benchmark suite. We report the average per-scene runtime for our method (3PT) alongside relevant baselines. We note that direct comparisons are complicated by hardware heterogeneity (e.g., H100 vs. RTX 4090) and differing input modalities (RGB vs. RGB-D).

However, several key trends emerge regarding the computational characteristics of 3PT:

**Scaling with No. Parts and Image Size.** 3PT’s detection runtime is primarily influenced by the image resolution (due to our sliding-window tiling strategy) and the size of the 3D object library. This is evident in *HOT3D*, where high-resolution inputs ( $2048 \times 2048$ ) and a larger object vocabulary (33 parts) result in higher detection latency (10.9s) compared to compact datasets like *LMO* (0.7s). In our demos we only run for a single-object, so runtimes are much faster.

**Efficiency vs. Precision Trade-off.** While 3PT is slower than lightweight detectors like MUSE [10], this computational cost enables the 3D-conditioned reasoning required for state-of-the-art zero-shot generalization. Crucially, on the challenging *BOP-Industrial* datasets, 3PT is significantly faster than the top-performing baseline, FRT-Pose [59]. On *XYZ* and *ITODD-MV*, 3PT reduces runtime by a factor of roughly  $4\times$  to  $8\times$  compared to FRTPose, while relying solely on MV-RGB inputs rather than RGB-D.

**Standardized Evaluation.** We emphasize that the reported runtimes for 3PT utilize a fixed set of hyperparameters (e.g., multiple scale priors, unknown classes, top- $K$  hypotheses) across all datasets within a category (e.g. Industrial) to ensure a fair, "out-of-the-box" evaluation. In practical deployments, these thresholds can be tuned to significantly accelerate inference. For example, in bin-picking, we use a single-object class, a single scale prior, a limited ROI, and only 3 cameras.

**Approximate Runtime.** The approximate runtime (GPU=H100, Batch=16) of 3PT-D is  $\sim 0.00636s \times T \times$

$I \times C$ . Where  $T$  = Tiles,  $I$  = Images, and  $C$  = 3-D object models. 3PT-R with 5 hypotheses and 3 iterations is  $\sim 0.078s \times O \times I$  where  $O$  = object instances detected (incl. false positives). For example, a typical IPD scene with  $I = 4, T = 8, C = 10, O = 70$  is  $\sim 24.7s$ . Or in the case of bin-picking, where  $I = 3, C = 1, T = 6$  we get  $\sim 11.8s$  for 50 objects, and  $\sim 1.26s$ . These equations aren’t exact since this assumes perfect batching and with a smaller number of objects we do not always achieve this, but it gives an good rough estimate.

**Code Optimizations.** Runtime can further be improved without algorithmic changes. Some of the code is not optimally implemented, for example the refinement could cache the image features across hypotheses since we run the same number of hypotheses across images.

### 6.6. Additional Limitations

This section outlines limitations related to input modalities and architectural design.

1. **RGB-D Integration:** While 3PT is designed to eliminate the dependency on depth sensors, there are scenarios where RGB-D is the only available modality or where depth data is high-quality. Currently, our framework does not leverage depth information. Extending the architecture to fuse depth features during the refinement stage could further enhance performance when multi-view is unavailable, and remains a promising direction for future work.
2. **Unified Architecture:** Although 3PT streamlines the pipeline compared to ensemble-based methods, it currently utilizes two separate models for detection (3PT-D) and refinement (3PT-R). A fully end-to-end trainable framework that unifies these stages into a single model could theoretically reduce feature redundancy and optimize inference efficiency.
3. **Texture Gap in 3D Models:** 3PT-D and 3PT-R are conditioned on renders of 3D object models. Consequently, performance degrades when there is a visual discrepancy between the provided CAD model and the physical object (e.g., texture mismatches or geometric simplifications), as observed in subsets of the IC-BIN dataset. While we achieve state-of-the-art performance on average, addressing these specific edge cases via render data augmentations during training is an area for future exploration. This limitation of being overly sensitive to subtle differences, however, can also be encouraged for certain applications. For instance, when sorting multiple similar objects, our approach is less prone to confusing them. A capability we demonstrate in [bin\\_picking.mp4](#).

### 6.7. Full Segmentation Results

As described in Sec. 3.3, 3PT-R generates per-instance 2D segmentation masks alongside the refined poses. On the

Table 5. Dataset statistics and runtime comparison. Runtimes are reported in seconds.

Metric	BOP-Classic							BOP-H3			BOP-Industrial		
	ITODD	LMO	YCB-V	T-LESS	HB	IC-BIN	TUD-L	HOT3D	HANDAL	HOPEv2	IPD	XYZ	ITODD-MV
No. Parts	28	8	21	30	33	2	3	33	40	28	10	15	28
No. Scenes	721	200	900	1000	300	150	600	5140	1684	457	1232	60	721
Image Size	960x1280	480x640	480x640	540x720	480x640	480x640	480x640	2048x2048	1440x1920	1080x1920	1544x2064	1080x1440	960x1280
RGB	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RGB-D	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓
MV-RGB	×	×	×	×	×	×	×	✓	×	×	✓	✓	✓
<i>Detection Runtime (seconds)</i>													
3PT (H100)	2.631	0.737	1.876	2.704	2.989	0.196	0.278	10.987	4.131	4.536	2.092	2.040	2.631
MUSE (4090)	0.406	0.585	0.446	0.519	0.465	0.556	0.559	0.722	1.038	0.995	0.688	0.671	0.406
<i>6DoF Pose Runtime (seconds)</i>													
3PT (H100)	6.941	4.768	5.261	14.079	10.043	2.443	1.540	18.224	14.522	15.292	24.516	42.138	24.979
Co-Op (4090)	3.368	12.113	6.313	9.295	9.090	11.352	9.561	1.958	3.237	4.864	—	—	—
FRTPose (5090)	—	—	—	—	—	—	—	—	—	—	93.013	160.484	230.962
FreeZeV2.2 (L40)	—	—	—	—	—	—	—	—	—	—	7.201	22.811	20.475

Table 6. 2D segmentation results for the BOP-Classic evaluation suite. While 3PT is the best algorithm on average, the majority of the improvement stems from the T-Less subset. We report Average Precision in %.

Method	LMO[4]	T-LESS[25]	TUD-L[28]	IC-BIN[16]	ITODD[18]	HB[33]	YCB-V[63]	Avg
CNOS [45]	39.7	37.4	48.0	27.0	25.4	51.1	59.9	41.2
SAM-6D [37]	46.0	45.1	56.9	35.7	33.2	59.3	60.5	48.1
MUSE [10]	47.7	47.8	57.3	43.3	39.1	63.5	69.0	52.5
Ours	47.4	64.0	56.0	31.9	43.1	68.0	64.7	53.6
$\Delta$	-0.3	+16.2	-1.3	-11.4	+4.0	+4.5	-4.3	+1.1

BOP-Classic benchmark suite (Tab. 6), 3PT achieves superior average performance compared to prior methods, though this improvement is largely attributed to its performance on the T-Less [25] subset.

## 6.8. Full Model-Free Detection Results

*Model-Free Detection* describes the scenario for 2D object detection (bounding box) where the object’s CAD model is not provided as an input to the system. This setting is common when CAD models are proprietary or unavailable. The system is instead provided with a gallery of input images (photographs) of the object, typically captured from viewpoints relevant to the application domain. We assume binary segmentation masks are available for each of these object images (as are available in the BOP challenge).

The 3PT-D framework is readily extendable to this model-free setting. As 3PT’s interaction with the CAD model is exclusively through the rendering pipeline, we adapt the framework by replacing any required synthetic rendering operation. Specifically, at each step where a render is needed, 3PT-D is modified to randomly select one of the provided masked photographs as the input.

The performance of this model-free adaptation is summarized in Tab. 7 on BOP-H3. BOP-Classic and BOP-Industrial do not have model-free benchmarks. We demonstrate significant performance gains on two out of the three evaluation datasets. Specifically, we achieve an 11.6 per-

Table 7. Comparison of detection methods. We report the Average Precision in %.  $\Delta$  denotes the raw percentage point difference w.r.t. the best competitor.

Method	HOT-3D	HOPEv2	HANDAL	Average
CNOS (FastSAM)	37.3	34.3	30.4	34.0
CNOS 25 (YOLOE-DINOv3)	48.1	45.2	38.9	44.1
Ours	45.8	56.8	41.9	48.2
$\Delta$	-2.3	+11.6	+3.0	+4.1

centage point improvement on HOPEv2 and exhibit a 4.1 increase on metric averaged across all tested datasets.

## 6.9. Dataset Curation

As mentioned in the paper, we trained the networks on 900,000 unique synthetic images, using over 100,000 mesh files. The dataset has approximately 100 million unique trainable object instances before data augmentation.

The CAD models were sourced from many different public datasets, including Objaverse[14], ABO[12], GSO[17], and OmniObject3D[62]. In addition to these meshes, we also use a different set of CAD models as distractor objects to help the network avoid false positive detections and to increase the diversity of the dataset.

For each image, we arranged the objects in one of three different ways: randomly oriented in mid-air, dropped onto a flat surface, and tightly packed together. The first arrangement ensures that the network would see the objects from a wide variety of angles. The second arrangement ensures that the data includes realistic occlusions and physically realistic poses. And the third arrangement helps the network differentiate between two objects extremely close together. It also produces realistic occlusions and simulates certain common real world scenarios.

Another important element being randomized is the material properties of the CAD models. For each instance, we apply a small jitter to its metallicness, roughness, and color





Figure 8. An example of a scene where objects have been dropped onto a surface into a dense pile.

properties. This helps the model be more robust to differences between the CAD prompts and the images of the object in the real world.

The dataset also features a wide variety of lighting conditions. In many of the scenes, we place directional and/or non-directional light sources with various colors and intensities. This simulates difficult light-related challenges found in the real world, such as shadows, non-uniform lighting, and extremely bright/dark conditions. To improve the realism of the lighting, we also leverage HDRI environments. Finally, we use Blender’s ray tracer to further improve the photorealism of the images.

## 6.10. Applications: AR Tracking

This section details the implementation and demonstration of the Augmented Reality (AR) tracking application introduced in Sec. 4.3 and Fig. 4(a) of the main paper.

We visualize our method on the *HOT3D* [1] dataset, which captures egocentric interaction scenarios using AR glasses. This dataset presents unique perception challenges: it relies on multi-view RGB (2 or 3 cameras depending on the device) with severe fisheye distortion and completely lacks depth sensor data [1]. The data consists of 5-second clips recorded at 30 fps (150 frames total).

To address this, we implement a detect-and-track pipeline. We employ the full 3PT framework to detect and estimate the initial object pose on the first frame ( $t = 0$ ). For the subsequent 149 frames, we bypass the detection stage and exclusively utilize the refinement module (3PT-

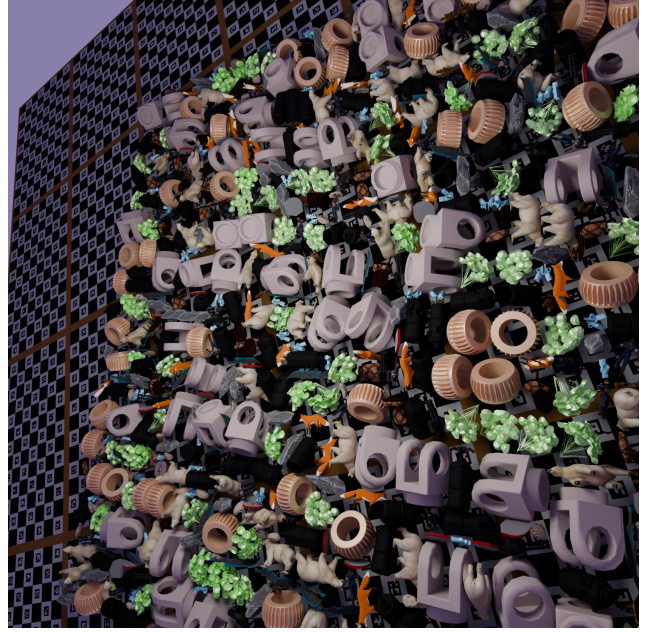


Figure 9. An example of a scene where objects are tightly packed together.

R) to update the pose. Specifically, we run a single iteration of 3PT-R on the multi-view inputs, initialized with the pose from the previous time step. This lightweight update operates at approximately 35ms per frame on an NVIDIA H100 GPU. The resulting high-stability tracking is visualized in the supplementary video *AR\_Tracking.mp4*.

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