Uni6D: A Unified CNN Framework without Projection Breakdown for 6D Pose Estimation

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Abstract

As RGB-D sensors become more affordable, using RGB-D images to obtain high-accuracy 6D pose estimation results becomes a better option. State-of-the-art approaches typically use different backbones to extract features for RGB and depth images. They use a 2D CNN for RGB images and a per-pixel point cloud network for depth data, as well as a fusion network for feature fusion. We find that the essential reason for using two independent backbones is the “projection breakdown” problem. In the depth image plane, the projected 3D structure of the physical world is preserved by the 1D depth value and its built-in 2D pixel coordinate (UV). Any spatial transformation that modifies UV, such as resize, flip, crop, or pooling operations in the CNN pipeline, breaks the binding between the pixel value and UV coordinate. As a consequence, the 3D structure is no longer preserved by a modified depth image or feature. To address this issue, we propose a simple yet effective method denoted as Uni6D that explicitly takes the extra UV data along with RGB-D images as input. Our method has a unified CNN framework for 6D pose estimation with a single CNN backbone. In particular, the architecture of our method is based on Mask R-CNN with two extra heads, one named RT head for directly predicting 6D pose and the other named abc head for guiding the network to map the visible points to their coordinates in the 3D model as an auxiliary module. This end-to-end approach balances simplicity and accuracy, achieving comparable accuracy with state of the arts and 7.2× faster inference speed on the YCB-Video dataset.

1. Introduction

6D pose estimation plays a fundamental role in emerging applications, e.g., autonomous driving [1–3], intelligent robotic grasping [4–6] and augmented reality [7]. RGB-D sensors provide a direct signal of the surface texture and geometry of the physical 3D world, and as their prices fall,
RGB-D images are becoming a more attractive data source for 6D pose estimation.

However, state of the arts [2,9–13] typically use two separate backbone networks to extract features for RGB and depth images, with a 2D CNN for RGB images and per-pixel PointNet [14] or PointNet++ [15] for depth data. After these features have been obtained, an additional fusion process is designed to blend them. Existing methods use different backbones to account for the heterogeneity of these two types of data. However, the key reason they can’t extract features with a single backbone is hidden in the classic 3D vision projection equation:

\[
\begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix} = K \begin{bmatrix}
  x \\
  y \\
  d
\end{bmatrix} \frac{K}{R_z(a, b, c) + T_z} \left( R \times \begin{bmatrix}
  a \\
  b \\
  c
\end{bmatrix} + T \right),
\]

which describes a point \((a, b, c)^1\) first rotated by the rotation matrix \(R \in SO(3)\) and translated by \(T \in \mathbb{R}^3\) to the position \((x, y, d)\) in camera coordinate system. It is then projected to the pixel at \((u, v)\) in image plane using the intrinsic matrix \(K\) of the camera. The 3D structure of the visible points in the 3D model seen from the camera’s perspective is preserved by the depth value \(d\) of each pixel and its coordinate \((u, v)\) in the depth image. It implies in a single-channel depth image, each pixel value is linked to its built-in coordinates. The plain UV can be used to preserve the 3D structure and changing it will break the 3D projection equation. However, in the traditional CNN pipeline, spatial transformations such as pooling, crop, RoI-Align [8] in the convolution operator, and resize, crop, and flip in data augmentation do change the UV. As shown in Fig. 1a, when those spatial transformations are applied to a depth image, the projection equation is broken, and we call this “projection breakdown”. This is the primary reason why the traditional CNN pipeline struggles to process RGB images and depth data at the same time.

In this paper, we propose a simple yet effective method to save the projection breakdown: explicitly feeding extra UV data along with depth to 2D CNN. D+UV acts as 3D to save the projection breakdown: explicitly feeding extra depth data at the same time.

To summarize, the main contributions of this paper are as follows: (1) We expose the “projection breakdown” problem that exists beneath CNN-based depth image processing and introduce the extra UV data into input to fix it, which indicates that a single CNN backbone is all you need for RGB-D feature extraction. (2) We propose an efficient and effective method denoted as Uni6D. The proposed abc head and RT head are optimized in a multitask manner, and we use RT head to directly obtain the pose estimation results. (3) We provide extensive experimental and ablation studies to highlight the benefits of our method, and the results show that our method outperforms existing methods in terms of the time efficiency and achieve promising performance.

2. Related Work

2.1. 6DoF Pose Estimation from RGB Images

Holistic methods, keypoint-based approaches and dense correspondence methods are the three types of RGB-only pose estimation methods. Holistic methods [18–26] directly estimate the 6D pose of objects in an RGB image. They use rigid templates to compute the best match pose or directly regress the 6D pose with deep neural networks. However, non-linearity of the rotation space limits generalization ability of DNN based methods. On the contrary, keypoint-based approaches [27–31] detect the keypoints of objects and then estimate the pose by finding the 2D and 3D correlations at these points. Dense correspondence methods [32–40] utilize the correspondence between image pixels and mesh vertexes to estimation the pose with the Perspective-n-Point (PnP) method to recover poses. Although these dense corre-

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1 We refer a point by its coordinate in object coordinate system.
spondence method can improve robustness in occlusion situations, the performance is damaged by the unlimited output space. However, the performance of all these methods which only uses RGB images are limited by the loss of geometry information. Therefore, many point clouds based methods have been proposed.

2.2. 6DoF Pose Estimation from Point Clouds

As the cost of depth sensors decreases and accuracy increases, several point clouds based methods have been proposed. The mainstream methods usually use 3D ConvNets [41, 42] or point cloud network [43, 43] to extract the feature and estimate the 6D pose. However, the performance of these methods are limited by the essential noise and shortcomings of the point clouds data. They do not perform well with the sparse and weakly textured point cloud, which indicates the necessity of RGB data.

2.3. 6DoF Pose Estimation from RGB-D Data

Recently, most of 6D pose estimation state-of-the-art approaches utilize the RGB images and depths or point cloud data to achieve a higher accuracy. Classical methods [33, 34, 44–48] adopt the correspondence grouping and hypothesis verification for the rule based feature and templates of RGB-D data. With the development of deep learning, most data-driven methods use deep neural networks to extract features instead of hand-coded features. They extract features of RGB images and point clouds with independent feature extractors and then fuse them. Most of them [2, 9–11, 16] use 2D CNN for RGB images and point cloud network for depth data considering the data heterogeneity between them. Since the appearance and geometry features are extracted separately, they need to add more complex structure to iterative fuse two features into one in order to predict poses [9–11, 16] and enable the communication between the RGB and depth information [16].

2.4. Analysis on State-of-the-art Approaches

As far as we know, the best result is obtained by two keypoint-based approaches, PVN3D [6] and FFB6D [16] for now. As the name implies, keypoint-based approaches design a network to predict the 3D offset from a visible point to some selected keypoints. Based on this offset, each visible point gives a prediction of keypoints in the camera coordinates system, i.e. \((x, y, z)\). An iterative voting mechanism is designed [6] to find the best prediction of keypoints by choosing the clustering with most votes. The coordinates of the keypoints, i.e. \((a, b, c)\) in 3D model, is known before inference. Given some matched pairs of \((a, b, c)\) and \((x, y, z)\), an iterative least-square regression is adopted to get the final 6D pose. We believe that the success of keypoint-based approaches is relies on two reasons: 1) Dense prediction and intelligent de-noising: each visible point will give prediction to visible points and voting is used to filter out bad predictions. Given depth images contain a lot of noise, voting is a great way of de-noising. 2) The 3D offset loss is useful to guide the network mapping visible points to its 3D model at pixel level.

PointNet++ [14, 15] requires finding K-nearest neighbors in 3D space. We believe KNN for each pixel, iterative voting and regression are quite heavy when porting to real applications. We find that the essential reason is the aforementioned projection breakdown caused by the change operation on UV. In our work, we reveal and solve the projection breakdown problem and adopt a unified feature extractor of the RGB-D data. Benefited from a unified CNN backbone to extract feature from RGB-D images, we propose a straightforward 6D pose estimation pipeline which directly outputs the detection and pose estimation in an end-to-end manner instead of using time-consuming post-processes.

3. Methodology of the Uni6D

Our goal is to propose an accurate, real-time and practical 6D pose estimation method. To this end, we develop an end-to-end framework named Uni6D, which extracts the feature of RGB-D images through a unified backbone network and directly outputs the 6D pose with a straightforward pipeline. Our framework inherits the concise design of Mask R-CNN [8] and introduces a novel RT head and an abc head into it to obtain the 6D pose. With these two heads, we perform multitask joint optimization for the object classification, detection, segmentation and pose estimation. The overall proposed architecture is illustrated in Fig. 2. In this section, we discuss how to inherit the legacy of the Mask R-CNN (Section 3.1), how to encode UV to fix the projection breakdown (Section 3.2), the structure of the RT head and abc head (Section 3.3), the loss function (Section 3.4) and the inference process (Section 3.5).

3.1. Legacy of Mask R-CNN

Object detection and instance segmentation are usually the first steps in 6D pose estimation. As a widely used practical algorithm, Mask R-CNN is capable of achieving them with satisfactory results. Therefore, we use the Mask R-CNN as the basic network. As shown in Fig. 2, Uni6D inherits the basic network structure from Mask R-CNN, including the ResNet [49] backbone, the FPN [50] for feature pyramid, the RPN to propose RoIs of potential objects, a mask head for segmentation, and a bbox head for object detection and classification. Using one backbone for two heterogeneous data becomes possible after we solve the projection breakdown problem. As a result, rather than using separate backbone networks for RGB images and depth data as in other methods, we simply use a unified backbone network that can be implemented by making minor changes to Mask R-CNN. Furthermore, feature fusion is no longer re-
Figure 2. Overview architecture of our Uni6D, which inherits the basic network structure and the simplicity from Mask R-CNN. We add the RGB-D, UV encoding and NRM with PE in a channel-wise manner and feed this new input into the single backbone network. No fusion operation for RGB and depth feature is further required. The red part in the backbone network denotes the channel modification to adapt the RGB-D+UV+NRM (with PE) input, which is to increase the input channel of the first convolutional layer. RT head is used to predict rotation and translation directly and abc head aims to map visible points to their 3D coordinate in its 3D model. With above components, our Uni6D predicts object categories, localization and its RT matrix directly without any post-processing.

3.2. Encoding UV Data as Input

To overcome the issue of projection breakdown, we add the UV data into the input RGB-D data and feed them together into the unified backbone. For the RGB-D data, we directly combine the RGB image and corresponding depth data along the channel dimension. There are three ways to encode positional information. 1) Plain UV coordinates UV: we directly concatenate these coordinates data with the RGB-D data along the channel dimension. Plain UV is the same height and width with RGB-D images. It has two channels, one channel stores the coordinate of U and the other V, i.e., the value at pixel \((u, v)\) in U-channel is \(u\), and in V-channel is \(v\). 2) Inverse projected XY: given camera intrinsic matrix \(K\) and depth image, we encode corresponding plain UV coordinates \((u, v)\) of each pixel into inverse projected XY \((x, y)\) based on Equation 1. XY has two channels, too. We also concatenate XY with RGB-D data along the channel dimension. 3) Positional encoding PE [51, 52]: positional encoding is widely used in many other fields such as vision transformers [52]. We encode the position with the trigonometric function and add it into the input data. Overall, the aforementioned three forms of UV encoding information have their own advantages. Plain UV is more direct, XY implies the internal reference information, and PE can be added to other input channels to be more integrated. They work together to complete each other and get the best performance. Since depth normal vector is a widely used for depth image, we also concatenate it to the input and denote it as “NRM”.

3.3. RT head and abc head for Multitask Learning

We propose RT head and abc head to predict RT matrix and the points of 3D model, where \(R\) is the rotation matrix in the form of quaternion and \(T \in \mathbb{R}^3\) is the translation matrix. These heads are added to Mask R-CNN as two novel parallel branches and take the features of all proposals extracted through RoI-Align as input. As shown in Fig. 3, the RT head in our method has a similar structure with the bbox head in Mask R-CNN, which contains two shared and two independent fully connected layers to obtain the RT matrix. The abc head is similar with the mask head as an FCN structure, which is developed with four \(3 \times 3\) and one \(1 \times 1\) convolutional layers to output the 3D points.
3.4. Loss Function

In addition to the classification, detection and segmentation loss functions in the original Mask R-CNN, there are two new loss functions for RT head and abc head. The formula of the RT head loss $L_{rt}$ is:

$$L_{rt} = \frac{1}{m} \sum_{x \in \mathcal{O}} ||(Rx + T) - (R^*x + T^*)||,$$  \hspace{1cm} (2)

where $\mathcal{O}$ is the vertex set sampled from the object’s 3D model, $R$ is the rotation matrix and $T$ is the translation vector. The loss of abc head is:

$$L_{abc} = |a - a^*| + |b - b^*| + |c - c^*|, \hspace{1cm} (3)$$

where $(a, b, c)$ are the coordinate of points. Thus, the overall loss function is:

$$L = \lambda_0 \cdot L_{rt} + \lambda_1 \cdot L_{abc} + \lambda_2 \cdot L_{mask} + \lambda_3 \cdot (L_{bbox} + L_{cls}) + \lambda_4 \cdot L_{rpn}, \hspace{1cm} (4)$$

where $\lambda_0, \lambda_1, \lambda_2, \lambda_3$ and $\lambda_4$ are the weights for each loss.

3.5. Inference

Different with other state of the arts of 6D pose estimation, our method does not use any additional time-consuming post-processing and directly outputs the estimation results from the RT head. The straightforward pipeline of our method significantly improves its inference efficiency and practicality. Corresponding quantitative results of estimation accuracy and time efficiency are shown in Section 4.3.

4. Experiments

4.1. Benchmark Datasets

To evaluate our method, we perform experiments on three 6D pose estimation datasets, including YCB-Video, LineMOD and Occlusion LineMOD.

YCB-Video [17] includes 92 videos with a variety of textures and shapes of RGBD data from 21 YCB objects. All of this data is annotated with 6D poses and instance-level masks. We follow previous work [6, 11, 53] to split the training and testing dataset. We also take the synthetic images for training through the same method in [53] and apply the hole completion algorithm used in [6] for hole filling to the depth images.

LineMOD [44] contains 13 videos of 13 low-textured objects with the annotation of 6D pose and instance-level mask. We follow previous work [30, 53] to split the training and testing sets, and we also obtain synthesis images for the training set as the same with [6, 53].

Occlusion LineMOD [33] is extracted from the LineMOD dataset to evaluate the robustness under heavily occluded situations.

4.2. Evaluation Metrics

We evaluate our method following [11, 16, 53] with the average distance metrics ADD and ADD-S. The ADD metric calculates the point-pair average distance between objects vertexes transformed by the predicted pose $[R, T]$ and the ground truth pose $[R^*, T^*]$: \[ADD = \frac{1}{m} \sum_{x \in \mathcal{O}} ||(Rx + T) - (R^*x + T^*)||,\]  \hspace{1cm} (5)

where $x$ indicates the vertex sampled from the object’s 3D model. ADD-S is applied to symmetric objects based on the closest point distance:

$$ADD-S = \frac{1}{m} \sum_{x_1 \in \mathcal{O}, x_2 \in \mathcal{O}} \min ||(Rx_1 + T) - (R^*x_2 + T^*)||. \hspace{1cm} (6)$$

For YCB-Video dataset, we follow [6, 11, 16, 53] to compute the ADD-S and ADD(S) under the accuracy-threshold curve obtained by varying the distance threshold with maximum threshold 0.1 meter (ADD-0.1). For LineMOD dataset, we follow [16, 30] to report the accuracy of distance less than 10% of the objects’ diameter (ADD-0.1d).

4.3. Quantitative Comparison with Other Methods

We compare the proposed method with others on YCB-Video, LineMOD, and Occlusion LineMOD datasets. Experimental results of YCB-Video dataset are reported in main paper and the results of LineMOD and Occlusion LineMOD are in Appendix.

**Evaluation results on YCB-Video dataset.** We report the quantitative results of the proposed Uni6D on YCB-Video dataset in Table 1. In comparison to other methods, our approach achieves 95.2% on the ADD-S metric and 88.8% on the ADD(S) metric with a succinct and straightforward pipeline. Although the previous method DenseFusion [11] does not use post-processing like our method, our
Table 1. Evaluation results (ADD-S AUC, ADD(S) AUC) on the YCB-Video dataset. Symmetric objects are denoted in bold.

| Object                | PoseCNN [53] | DenseFusion [11] | PVN3D [6] | FFB6D [16] | Ours |
|-----------------------|--------------|------------------|-----------|------------|------|
| 002_cracker_chef_can | 83.9         | 50.2             | 95.3      | 70.7       | 96   |
| 003_cracker_box      | 76.9         | 53.1             | 92.5      | 86.9       | 96.1 |
| 004_sugar_box        | 84.2         | 68.4             | 95.1      | 90.8       | 97.4 |
| 005_sugar_soup_can   | 81.0         | 66.2             | 93.8      | 8.47       | 96.2 |
| 006_mustard_bottle   | 90.4         | 81.0             | 95.8      | 90.9       | 97.5 |
| 007_juice_fish_can   | 88.0         | 70.7             | 95.7      | 79.6       | 96.0 |
| 008_pudding_box      | 79.1         | 62.7             | 94.3      | 89.3       | 97.1 |
| 009_gelatin_box      | 87.2         | 75.2             | 97.2      | 95.8       | 97.7 |
| 010_potted_meat_can  | 78.5         | 59.5             | 89.3      | 79.6       | 93.3 |
| 011_fan              | 86.0         | 72.3             | 90.0      | 76.7       | 96.6 |
| 012_pitcher_base     | 77.0         | 53.3             | 93.6      | 87.1       | 97.4 |
| 013_bread             | 71.6         | 50.3             | 94.4      | 87.5       | 96.0 |
| 024_bowl             | 69.6         | 69.6             | 86.0      | 86.0       | 90.2 |
| 025_mug              | 78.2         | 58.5             | 95.3      | 83.8       | 97.6 |
| 035_power_drill      | 72.7         | 55.3             | 92.1      | 83.7       | 96.7 |
| 036_wood_block       | 64.3         | 64.3             | 89.5      | 89.5       | 90.4 |
| 037_scissors         | 56.9         | 35.8             | 90.1      | 77.4       | 96.7 |
| 040_jar              | 71.7         | 58.3             | 95.1      | 89.1       | 96.7 |
| 051_large_clamp      | 50.2         | 50.2             | 71.5      | 71.5       | 93.6 |
| 052_extra_large_clamp| 44.1         | 44.1             | 70.2      | 70.2       | 88.4 |
| 061_foam_brake       | 88.0         | 88.0             | 92.2      | 92.2       | 96.8 |
| Avg                   | 75.8         | 59.9             | 91.2      | 82.9       | 95.5 |

Table 2. Time cost and frames per second (FPS) on YCB-Video Dataset. Our Uni6D is 7.2× faster than FFB6D, and 13.6× than PVN3D. It is capable of estimating 6D pose in real-time. Note that the results of PoseCNN and DenseFusion comes from [11], which does not state their device type.

| Method          | Network | Post-process | ALL | FPS  |
|-----------------|---------|--------------|-----|------|
| PoseCNN+ICP     | 200     | 10400        | 10600| 0.094|
| PoseCNN         | 200     | 0            | 200  | 5    |
| DenseFusion     | 50      | 10           | 60   | 16.67|
| PVN3D           | 110     | 420          | 530  | 1.89 |
| FFB6D           | 20      | 260          | 280  | 3.57 |
| Ours            | 39      | 0            | 39   | 25.64|

Figure 4. Performance of difference approaches under increasing level of occlusion on YCB-Video Dataset. Our per-RoI method is effective at identifying and handling occlusion.

method improves the ADD-S by 4%. In contrast to DenseFusion, which requires two different backbones, CNN and PointNet [14], our method only needs a unified CNN to extract RGB-D features. It is worth emphasizing that although the performance of our method is a little bit lower than the current state-of-the-art methods [6, 16], it does not use any additional iterative refinement and post-process operations which are required in state-of-the-art methods. We discuss the time efficiency of our method below. Following [11,16], we also evaluate the robustness towards occlusion in YCB-Video dataset through calculating how the accuracy (ADD-S < 2cm) changes with extent of occlusion. As indicated in Fig. 4, the performances of our methods has the minimal drop compared with DenseFusion [11] and FFB6D [16]. In particular, the performance under increasing level of occlusion decrease by 0.3%, which is comparable to FFB6D. Occlusion should be better identified and handled because our RT prediction is based on a RoI.

Time efficiency. To highlight the inference efficiency of our straightforward pipeline, we compare the inference speed of our method with PoseCNN+ICP [53], PoseCNN [53], DenseFusion [11], PVN3D [6] and FFB6D [16] in Table 2. Post-processing accounts for 92.9% of the total time in FFB6D and 79.2% in PVN3D. DenseFusion has a faster inference speed compares to them, while our method further speeds up the inference, benefited from our straightforward pipeline which does not need any post-
4.4. Implementation Details

In all experiments, we adopt ResNet-50 [49] as the backbone network with FPN [50]. We train all models with 16 GPUs (three images per GPU) for 40 epochs with an SGD optimizer which momentum is 0.9 and weight-decay is 0.0001. The initial learning rate is set to 0.0075 with a linear warm-up, and decreased by 0.1 after 15, 25 and 35 epochs. The weight hyperparameter $\lambda_0$ in the loss function of RT head is set to 1 in epoch $[1, 20)$, 5 in $[20, 30)$, 20 in $[30, 38)$ and 50 in $[38, 40)$.

4.5. Ablation Study

4.5.1 Projection Breakdown Saved by UV

To investigate the effects of the UV encoding information in the projection breakdown problem, we perform experiments with several spatial transformations on the YCB-Video dataset in Table 3. Using any of the common spatial transformations as training augmentation methods, such as random resize, crop, horizontal flip, and vertical flip, significantly reduces performance by up to 15% ADD-S and 20% ADD(S). These results directly reflect the destructiveness of projection breakdown. We add explicit UV encoding information with UV, XY, NRM, or PE to solve this issue and make the one backbone is all you need possible.

4.5.2 UV Encoding Methods

We investigate the contributions of all components in UV encoding of our method on the YCB-Video dataset. The results are shown in Table 4. “RGB-D” denotes that we only use RGB-D data as input, which is used as the baseline. “Plain UV” means the plain UV coordinates data. “XY” represents adding the inverse projected XY coordinates data. “NRM” means the depth normal vector. “PE” is the position encoding. “abc head” denotes adding the abc head during training. We can see that the flip transformation degrades performance in the baseline, and that adding position information to the RGB-D data in the form of plain UV, XY, NRM, or PE can alleviate this degradation. Compared with the baseline, our method brings 4.19% improvement in ADD-S and 9.11% in ADD(S).

4.6. Qualitative Results

For intuitively comparing the qualitative results between our Uni6D and other methods [6, 16] on the YCB-Video dataset, we give some estimation results in Fig. 6. Our Uni6D significantly outperforms the state of the art and performs the most robust in different occlusion situations.

5. Limitation Analysis

In this section, we discuss the limitations of our method. For the performance of 6D pose estimation, our method still has a little gap compared with the state of the art in YCB dataset. The main reason is that we do not use any time-consuming post-processing or iteration refinement in the pipeline of our method. We only add a lightweight abc head with the abc regression task to introduce an auxiliary loss for auxiliary model training. In inference, the abc head is removed and we directly obtain the 6D pose estimation results from the RT head. This straightforward inference pipeline significantly improves the efficiency of inference and reduces the difficulty of engineering implementation. It is worth exploring more efficient post-processing algorithms for our unified 2D CNN to further improve the performance while maintaining real-time inference.

For the RoI-Align operation, it limits the performance of RT head and reduces the accuracy of our method. The training and testing of our end-to-end method is applied in a RoI-wise manner with a rough object-level feature for each...
Table 4. Effects of each component in our work. Results of ADD(S) AUC and ADD-S AUC on YCB-Video are reported respectively. Compared with the baseline, our method brings 4.19% improvement in ADD-S and 9.11% in ADD(S).

| RGB-D | Plain UV | XY | PE | NRM | abc head | ADD-S | ADD(S) |
|-------|----------|----|----|-----|----------|-------|--------|
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 90.99 | 79.72  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 94.06 | 85.39  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 93.54 | 85.05  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 93.79 | 84.79  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 93.90 | 85.06  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 93.27 | 84.49  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 93.65 | 84.51  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 94.70 | 86.76  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 94.26 | 85.52  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 93.31 | 83.42  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 93.55 | 84.83  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | 94.91 | 86.93  |
| ✓     | ✓        | ✓  | ✓  | ✓   | ✓        | **95.18** | **88.83** |

6. Conclusions

In this paper, we reveal the “projection breakdown” hidden underneath CNN-based depth image processing, which explains the two-backbone design for RGB-D processing and the per-pixel feature extraction for depth processing adopted by most of the existing literature. Rather than using two separate backbones, we fix the projection breakdown by explicitly feeding extra UV data along with depth to the backbone. As a result, all you need to extract the feature from RGB-D images is a general 2D CNN backbone. Thus, we propose Uni6D, an end-to-end 6D pose estimation framework based on Mask R-CNN. Uni6D uses ResNet and FPN as its backbone to extract features from RGB-D images, extra feature fusion is not required anymore. The 6D pose estimation results are obtained directly from the RT head using a straightforward inference pipeline that does not require any time-consuming post-processing. We also develop the abc head as an auxiliary task for training the network in our framework. Extensive experimental results show our method outperforms other state-of-the-art methods in terms of time efficiency, performance, and robustness in the challenging YCB-Video. Worthwhile and related future work can be spawned from the proposed new 6D pose estimation paradigm, which performs 6D pose estimation with a unified CNN framework with the above contributions.

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