

# CrossInfoNet: Multi-Task Information Sharing Based Hand Pose Estimation

Kuo Du<sup>1</sup> Xiangbo Lin<sup>2\*</sup> Yi Sun<sup>2</sup> Xiaohong Ma<sup>2</sup>  
Dalian University of Technology, China

<sup>1</sup>dumyy2728@mail.l.dlut.edu.cn, <sup>2</sup>{linxbo, lslwf, maxh}@dlut.edu.cn

## Abstract

*This paper focuses on the topic of vision based hand pose estimation from single depth map using convolutional neural network (CNN). Our main contributions lie in designing a new pose regression network architecture named CrossInfoNet. The proposed CrossInfoNet decomposes hand pose estimation task into palm pose estimation sub-task and finger pose estimation sub-task, and adopts two-branch cross-connection structure to share the beneficial complementary information between the sub-tasks. Our work is inspired by multi-task information sharing mechanism, which has been few discussed in hand pose estimation using depth data in previous publications. In addition, we propose a heat-map guided feature extraction structure to get better feature maps, and train the complete network end-to-end. The effectiveness of the proposed CrossInfoNet is evaluated with extensively self-comparative experiments and in comparison with state-of-the-art methods on four public hand pose datasets. The code is available in<sup>1</sup>.*

## 1. Introduction

The research of vision based 3D hand pose estimation is a hotspot in the field of computer vision, virtual reality and robotics. It has been studied for decades and has made significant progress in recent years [3, 6, 19]. Nevertheless, it is still far from a solved problem due to the challenges of high joint flexibility, local self-similarity and severe occlusions. Different efforts have been made in vision based hand pose estimation. The input data changed from single RGB [2, 7], stereo RGB [24, 27], to depth maps which have made many achievements [26, 30, 39]. Recently, there seems to be a renewed interest to RGB images [24, 48, 18, 25]. The published hand pose estimation methods can be categorized into two main categories as either generative model-based [29, 35] or discriminative learning-based methods [11, 32, 36, 38]. Benefit from the increase of data amounts and computational ability, deep

CNN has showed strong abilities and has become the leading method at present.

In 2017, Hands in the Million Challenge (HIM2017) [44] on depth maps based hand pose estimation attracted the attentions of many research teams. The issues discussed in the competition summary paper [43] are also our concerns.

Firstly, treating depth maps as 2D images and regressing 3D joint coordinates directly is a commonly used hand pose estimation pipeline. Although converting the 2.5D depth maps into 3D voxelized forms will reserve more information [12, 17], it suffers from heavy parameter loads and still exists information defect. In our work, we tend to be in line with the argument of [39] to leverage the advances of 2D CNNs, and try to excavate more information from 2D inputs.

Secondly, designing effective networks receives the most attentions. In machine learning, by sharing information, multi-task learning has the advantages of reserving more intrinsic information than single task learning. Learning multiple tasks simultaneously will be helpful to enforce a model with better generalizing ability [28]. However, multi-task learning has not been paid enough attention in CNN based hand pose estimation yet. As [39] claimed, they did the first attempt to fuse the hand pose estimation results of the holistic regression and the heat-map detection in a multi-task setup. Inspired by their achievements, we design a new CNN structure for hand pose estimation in a multi-task setup. Hierarchical model is one of hand pose estimation networks and has shown excellent performance in competition. It usually divides the pose estimation problem into sub-tasks by separately dealing with different fingers or different type of joints [4, 16, 47]. Intuitively, it would be easily understood that palm joints have closer tie-ups than those more flexible finger joints. The global hand pose will be mostly determined by the status of the palm joints, while the local hand pose will be reflected by the actions of the finger joints. Based on these knowledge, we design a new hierarchical model in a multi-task setup. The proposed architecture has two branches corresponding to the palm joint regression sub-task and the finger joint regression sub-task, respectively. By cross-connections between

<sup>1</sup><https://github.com/dumyy/handpose>

the two branches, the noise in one branch becomes supplemental enhancement information in the other branch. This will help each branch to focus on its specific sub-task as is done in multi-task information sharing.

Thirdly, the output representations can be classified into the probability density map (heat-maps) or the 3D coordinates for each joint. Since the mapping between the 2D depth maps and the 3D joint coordinates is highly nonlinear, it will hamper the learning procedure and prevent the network from accurately estimating the joint coordinates. In contrast, the output representation with the heat-maps can provide more joint related information than a single joint location, which will help the network to get better feature maps. The analysis in [43] has concluded that the heat-map based method outperforms direct coordinate regression method. However, in heat-map based method, the final joint coordinates have usually to be inferred by maximum operation on the heat-maps. Maximum operation is non-differentiable, and it has to be tailored as a post-processing step, but not an end-to-end training. Taking into account of the advantages of the two representations, we propose a heat-map guided feature extraction network structure. In fact, our idea skillfully applies the multi-task parameter sharing.

In summary, for deep CNN based hand pose estimation from single depth map, our work has the following contributions:

- A new hand pose regression network in multi-task setup is proposed. It takes advantage of information sharing mechanism in multi-task learning. We use hierarchical model to decompose the final task into palm joint regression sub-task and finger joint regression sub-task. By branch cross-connection, the generated ‘attention mask’ guides one branch to focus on palm joint regression, and the other branch to focus on finger joint regression. Since the ‘attention mask’ enhances the sub-task features, the estimation accuracy is improved effectively.
- A heat-map guided feature extraction structure is proposed. It transfers more effective features from the heat-map detection task to the joint regressing task, without losing the end-to-end training advantage.
- We implement several baselines to investigate information sharing in a multi-task setup, which will provide valuable insights to this problem. We also carry out substantial experiments on commonly used datasets, and compare the performance with the state-of-the-art methods.

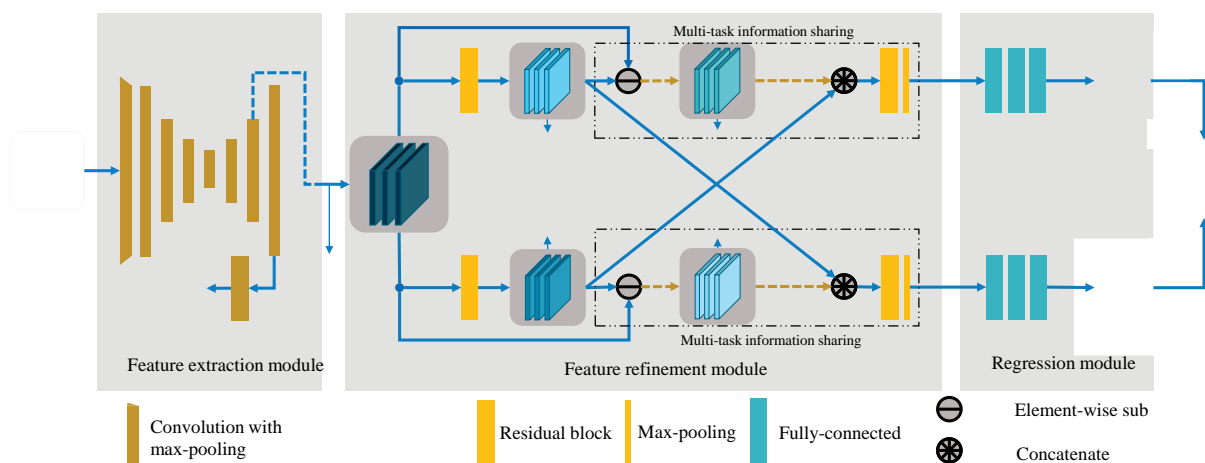
## 2. Related works

The achievements in vision based hand pose estimation are very rich. Since our work focuses on deep CNN based hand pose estimation from single depth map, we will limit the discussions to those works related closely with our work. Please refer to [8, 33, 43] for more comprehensive

reviews.

**Pose parameterization:** The object of hand pose estimation is to find the joint coordinates. Directly regressing these coordinates is the natural choice in the models for output pose representation [4, 10, 12, 22, 23, 46]. However, since only one 3D coordinate for each joint has to be regressed from the input, the highly non-linear mapping between the input and the 3D coordinates output hampers the learning procedure. To cope with this problem, Tompson *et al.* [38] firstly utilized 2D heat-maps for each hand joint as the pose parameters and then translated them into 3D coordinates by post-processing. They found that the intermediate heat-maps representation not only reduced required learning capacity but also improved generalization performance. Ge *et al.* [11] extended this method by exploiting multi-view CNN to estimate 2D heat-maps for each view. Moon *et al.* [17] adopted 3D heat-maps as the hand pose parameters. Wan *et al.* [39] decomposed the pose parameters into 2D heat-maps, 3D heat-maps, and unit 3D directional vector fields. Then these different outputs were translated into 3D joint coordinates by a vote casting scheme with a variant of mean shift post-processing. Different from their schemes, our work uses 3D coordinate regression under heat-map constraints. Such strategy can help the model to learn a better feature map, and get accurate joint coordinates without the need of post-processing.

**Model design:** Designing a network according to human hand kinematics or morphology has received competitive results in recent years [44]. Structured methods embed physical hand motion constraints into the model or in the loss function [16, 31, 46]. Hierarchical models divide the pose estimation problem into sub-tasks according to the hand structure. Chen *et al.* [40] applied constraints per finger and joint-type (across fingers) in their multiple regions extraction step, each region containing a subset of joints. The extracted feature regions were then integrated hierarchically and the hand pose were regressed by utilizing an iterative cascaded method. Madadi *et al.* [16] designed a hierarchically structured CNN, using five branches to model each finger and an additional branch to model the palm orientation. The final layers of all branches were concatenated into one layer to predict all joints. Zhou *et al.* [47] designed a three-branch network according to different finger functions in daily manipulation, where one branch correlated with the thumb finger, one branch modeled the index finger, and the last branch represented the other three fingers. These hierarchical models have their distinctive characteristics. Here we explore a new two-branch model with one branch for palm joint regression and the other branch for finger joint regression. It is a common sense that the finger joints are more flexible than the palm joints. If we use two different parameter sets to represent relatively stable palm pose and flexible finger pose separately, the regression task



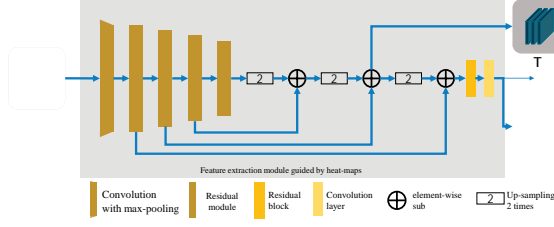


Figure 2. The initial feature extraction module. This network takes 2D depth map as input with the size of  $96 \times 96$  and outputs the feature maps  $T$  with the size of  $12 \times 12$ . We use 2D heat maps with the size of  $24 \times 24$  as supervision to guide the feature extractions.

### 3.1. Heat-map guided feature extraction

When a shallow CNN is used for feature extraction, the estimated results are usually not satisfactory. Given the problem, we design a novel feature extraction network with two stages, named as initial feature extraction module and feature refinement module. As for the initial feature extraction module, we choose the ResNet-50 [15] backbone network with four residual modules because it is highly efficient, as shown in Fig.2. In order to obtain more information, we apply the feature pyramid structure to merge different feature layers. We denote the feature maps for regressing initial joint locations as  $T$ . Different from previous heat-map based detection method, here the heat maps are only used as the constraints to guide the feature extraction and will not be passed to the subsequent module. The obtained feature map  $T$  with 256 channels will be input to the feature refinement module. The kernel size of the residual blocks is  $3 \times 3$ , and that of max-pooling layers is  $2 \times 2$  with stride 2. We use a convolution layer with  $3 \times 3$  filters to obtain the heat-map outputs for all joints.

### 3.2. Baseline feature refinement architecture

Some existing methods for hand pose estimation design tree-like branches, each of which is responsible for one independent sub-task, or extracts hand features from the output of one task to assist the other task at post-processing. They can neither extract powerful features nor strengthen the models. To fully utilize the extracted information, we proposed a novel feature refinement module based on multi-task information sharing. Before introducing our new multi-task feature refinement module, we first give the baseline multi-task architecture, which is illustrated in Fig.3.

Among all the joints, the palm joints have a smaller activity space compared to the finger joints, so the regressing complexity of the two parts is also different. If we use two different parameter sets to represent palm pose and finger pose, the hand pose would be regressed easier. Therefore, we separate the palm joint regression and finger joint regression into two independent branches. The feature maps

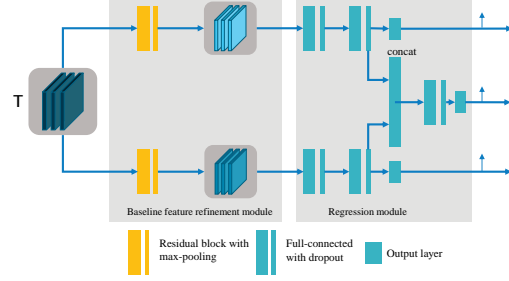


Figure 3. The baseline feature refinement module connected with the joint coordinate regression module. The kernel size of residual block is set to  $3 \times 3$  and the dimension of full-connected layer is set to 2048.

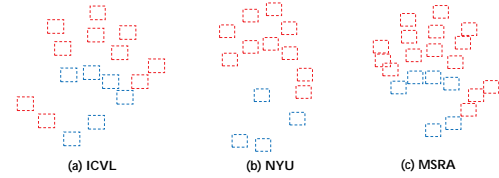


Figure 4. The palm joints subset (blue boxes) and the finger joints subset (red boxes) on different datasets.

$T$  from the initial feature extraction module are input to the residual block to extract more intrinsic local features of palm or fingers in different branch. Then the output of the full-connected layer  $f_p$  in the palm branch and  $f_f$  in the finger branch are concatenated to estimate all joint coordinates. We denote this architecture as the baseline network. Since ICVL, NYU and MSRA datasets have different label protocol, the joints subsets have some differences, as shown in Fig.4. The partition of HAND 2017 frame-based challenge dataset is the same as that of MSRA.

### 3.3. New feature refinement architecture

The baseline network only considers regressing palm and finger poses independently from each branch, which has no essential difference with the universal branch based network. There is little shared information between them, except the input features  $T$ . However, in the palm regression branch, there are residual finger features. These finger features may be noise for palm pose regression, but they are beneficial for finger pose regression. The same is in the finger branch. To make full use of the useful ‘noise’ information between the two branches, we try to design the network in a multi-task information sharing setup. Two-task Cross-stitch Network [28] is a universal multi-task network, as shown in Fig.5(a). It uses multiple cross-stitch units to leverage the knowledge of the other task by lazy fusion. Nevertheless, lazy cross-stitch may cause interference between sub-tasks, and lazy cross-stitch has no clear understanding of the sub-tasks – their similarity and rela-

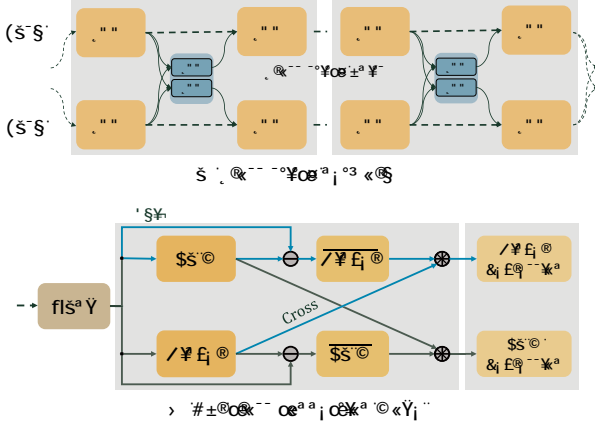


Figure 5. Network comparisons with Cross-stitch Network

tionships.

We hope to actively guide how the sub-tasks should interact with each other. By guided information sharing, the features related to the same targets should be merged and enhanced. Fig.5(b) illustrates the proposed multi-task information sharing mechanism. It uses “skip line” to separate palm and fingers (Finger) by subtracting the palm features from the global hand features, then uses cross line to concatenate the finger features from the two branches. It reduces the interference from the palm and enhances the finger features once more, and vice versa.

The detailed network structure is shown in Fig.6. Initial features  $T$  have palm related features and finger related features. By subtraction operation between  $T$  and palm pose dominated features  $P_0$  via skip-connection, we get residual finger features  $F_-$ , regarded as finger ‘attention mask’. This mask may be ‘noise’ for palm pose regression, but it will be beneficial for finger pose regression, which helps guide the branch to extract finer features. In the same way, we get the palm ‘attention mask’  $P_-$ . By cross-connection,  $P_0$  are concatenated with  $P_-$  and form the enhanced palm features  $P_1$ . The enhanced finger features  $F_1$  are also obtained using the similar process. In this way, our new network architecture establishes associations between the different sub-tasks. The output features  $F_2$  and  $P_2$  are got from the followed residual block. In the end, the 3D hand joint coordinates are estimated through the final regression module. The network parameters are presented in Fig.6, and the main pose regression procedure is described in Algorithm 1.

### 3.4. Loss functions

We adopt the mean square error between the ground-truth and the estimated joint coordinates as the loss function. In the initial feature extraction module, we use a heat map as the constraint to guide the network for a better global

### Algorithm 1 joint regression with multi-task information sharing.

**Input:**

Symbols:

: spatial convolution operator

: feature concatenation operator

$p_0, p_1$  : convolutional layers for palm feature extraction in different stages

$f_0, f_1$  : convolutional layers for fingers feature extraction in different stages

$f_c$  : Full-connected layers for regressing joint locations.

$T$  :  $T^{W \times H \times C}$ : regression feature

- 1:  $P_0 = T$   $p_0$ ;  $F_0 = T$   $f_0$  Preliminary features
- 2:  $F_- = T - P_0$ ;  $P_- = T - F_0$  Residual features
- 3:  $P_1 = P_0$   $P_-$ ;  $F_1 = F_0$   $F_-$  Enhanced features
- 4:  $P_2 = P_1$   $p_1$ ;  $F_2 = F_1$   $f_1$  The final features
- 5:  $J_p = f_c(P_2)$ ;  $J_f = f_c(F_2)$  The joint coordinates
- 6:  $J = J_p$   $J_f$  The final joint coordinates

**Output:**  $J$

feature extraction, so the detection loss of heat-map is defined as:

$$L_{ht} = \sum_{n=1}^A \sum_{u,v} (H_n^a(u, v) - H_n^e(u, v))^2 \quad (1)$$

where  $A$  denotes the joint number of the whole hand.  $H_n^a$  and  $H_n^e$  represent the ground-truth heat-map and estimated heat-map of joint  $n$ , respectively.

In the feature refinement module, we introduce two constraints,  $L_{bp}$  and  $L_{bf}$ , to extract the preliminary palm features  $P_0$  and finger features  $F_0$ . They are defined as:

$$L_{bp} = \sum_{n=1}^P \sum_{u,v} (H_n^p(u, v) - H_n^e(u, v))^2 \quad (2)$$

$$L_{bf} = \sum_{n=1}^F \sum_{u,v} (H_n^f(u, v) - H_n^e(u, v))^2 \quad (3)$$

where  $H_n^p$  and  $H_n^f$  represent the ground-truth heat map of the  $n$ th palm joint and finger joint, respectively.  $H_n^p$  and  $H_n^f$  are the corresponding network outputs.

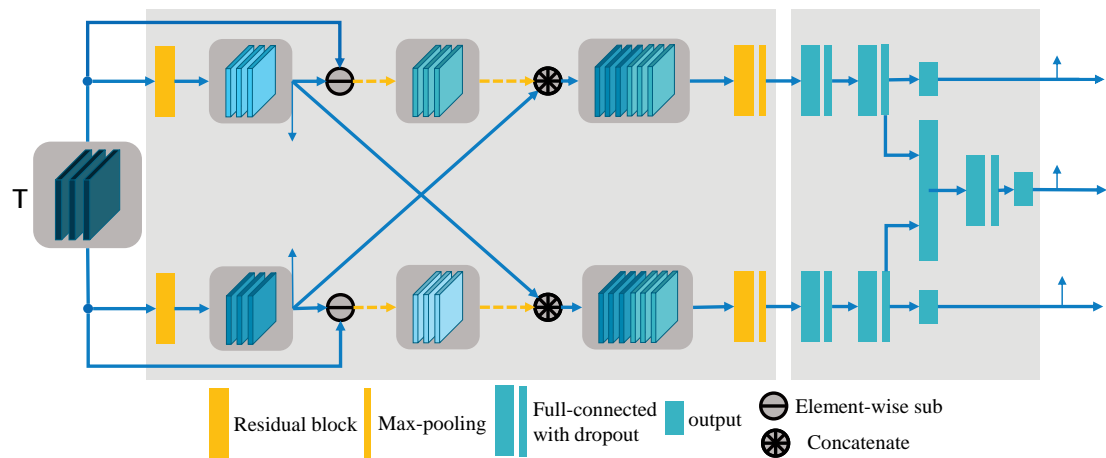
In the regression module, three losses are used to supervise the final outputs of each subtask and the total hand joints. They are palm joint regression loss  $L_{ep}$ , finger joint regression loss  $L_{ef}$ , and total hand joint regression loss  $L_a$ .

$$L_{ep} = \sum_{n=1}^P \|J_n^p - J_n^e\|_2^2 \quad (4)$$

$$L_{ef} = \sum_{n=1}^F \|J_n^f - J_n^e\|_2^2 \quad (5)$$

$$L_a = \sum_{n=1}^A \|J_n^a - J_n^e\|_2^2 \quad (6)$$

where  $J_n^p$  and  $J_n^f$  denote the ground-truth and estimated 3D coordinates of the  $n$ th palm joint,  $J_n^f$  and  $J_n^e$  are the



Strategy	Average 3D distance error (mm)	
	ICVL	NYU
Base	9.28	11.17
Base+HM	9.08	10.84
Cross	8.79	10.57
Cross+HM	8.48	10.08

Table 1. Self-comparison results on average 3D distance error (mm). Base: baseline network without the heat-map constraints; Base + HM: baseline network with the heat-map constraints; Cross: cross-connection network without the heat-map constraints; Cross + HM: cross-connection network with the heat-map constraints.

## 4.2. Self-comparisons

We conduct ablation experiments on both ICVL[34] and NYU[38] datasets. To evaluate the advantages of the heat-map constraints, we compared the results of baseline network with or without heat-map constraints. To demonstrate the performance of the multi-task information sharing network, we compared it with baseline network.

As shown in Tab.1, the baseline network with heat-map constraints reduces the mean 3D distance error by 0.2mm (from 9.28 to 9.08) on the ICVL dataset and by 0.33mm (from 11.17 to 10.84) on the NYU dataset, compared to the one without heat-map constraints. It proves that the heat-map constraints enforce the model to get better features and the estimated errors decrease. Then based on the initial feature extraction network with heat-map constraints, we compared the effect of two different feature refinement modules on the average 3D distance error. The proposed model with cross-connection significantly lowers the errors by 0.60mm (from 9.08 to 8.48) on the ICVL dataset and by 0.76mm (from 10.84 to 10.08) on the NYU dataset, compared to the one in the baseline model with two separated branches. Obviously, the result of this comparative experiment supports our viewpoint that multi-task information sharing can get more accurate hand pose estimation.

Based on the comprehensive self-comparisons, it can be concluded that the proposed model with multi-task information sharing via cross-connected two-branch architecture and heat-map guided initial feature extraction, has the best performance in hand pose estimation.

## 4.3. Comparisons with state-of-the-art methods

We compared the performance of the proposed Cross-InfoNet on three public 3D hand pose datasets with most of state-of-the-art methods, including methods using depth maps (2D) as inputs: latent random forest (LRF)[34], model-based method (DeepModel)[46], feedback loop training (Feedback) [23], Lie-X [42], DeepPrior with refinement (DeepPrior) [22], improved DeepPrior (DeepPrior++) [21], region ensemble network (Ren-4x6x6 [14],

Methods	Mean error (mm)			Input
	ICVL	NYU	MSRA	
Feedback [23]	-	-	15.97	2D
Lie-X [42]	-	-	14.51	2D
LRF [34]	12.58	-	-	2D
DeepModel [46]	11.56	17.04	-	2D
DeepPrior [22]	10.4	19.73	-	2D
Ren-4x6x6 [14]	7.63	13.39	-	2D
Ren-9x6x6 [40]	7.31	12.69	9.7	2D
DeepPrior++ [21]	8.1	12.24	9.5	2D
Pose-Ren [4]	6.79	11.81	8.65	2D
DenseReg [39]	7.3	10.2	7.2	2D
CrossInfoNet(Ours)	<b>6.73</b>	<b>10.08</b>	7.86	2D
3DCNN [12]	-	14.1	9.6	3D
SHPR-Net [5]	7.22	10.78	7.76	3D
HandPointNet [10]	6.94	10.54	8.5	3D
Point-to-Point [13]	6.3	9.1	7.7	3D
V2V [17]	<b>6.28</b>	<b>8.42</b>	<b>7.59</b>	3D

Table 2. Comparisons with state-of-the-art methods on three datasets. Mean error indicates the average 3D distance error.

Methods	Testing on single GPU (fps)
V2V [17]	3.5
DenseReg [39]	27.8
Point-to-Point [13]	41.8
CrossInfoNet (Ours)	124.5

Table 3. Comparison of inference time while testing.

Ren-9x6x6 [40]), Pose-guided REN (Pose-Ren) [4], dense regression network (DenseReg) [39], and methods using point cloud or voxel (3D) as input: 3DCNN [12], SHPR-Net [5], HandPointNet [10], Point-to-Point [13], V2V [17]. The results of some methods used for comparisons are obtained from the online available prediction labels, others are extracted from their papers.

As shown in Tab.2 and Fig.7, our results outperform the results of the state-of-the-art methods whose input is a depth map on ICVL and NYU datasets. Compared to those methods using 3D inputs, our results are worse than V2V [17] and Point-to-Point [13], but have larger improvement than 3DCNN [12] and SHPR-Net [5]. For the MSRA dataset, our method gets comparable results with the best 3D CNN method. DenseReg [39] is better than our method on this dataset. Nevertheless, when the threshold is below 10mm, our method is better on percentage of success frames metric. The qualitative results of our method on three datasets are shown in Fig.8.

Although on ICVL and NYU datasets, V2V and Point-to-Point methods with 3D input are better, and on MSRA dataset, DenseReg method with 2D input is better, they have a higher inference time on test data than our method. The

Figure 7. Comparisons with state-of-the-art methods. Top row: the percentage of good frames over different error thresholds. Bottom row: 3D distance errors per hand joints. Left: NYU [38] dataset. Middle: ICVL [34] dataset. Right: MSRA [32] dataset.

Figure 8. The qualitative results of our method on three datasets. Left: ICVL [34] dataset. Middle: NYU [38] dataset. Right: MSRA [32] dataset. Ground truth is shown in blue, and the estimated pose is shown in red.

comparisons about inference time are listed in Tab.3.

We also tested the performance of our method on the HANDS 2017 frame-based challenge dataset [44] on Feb.2, 2019. Our method won the first place, and had the best performance on the Unseen data.

## 5. Conclusion

Our work aims at exploring an effective CNN network to get the hand joint coordinates from depth data input. Our designed two-branch cross-connection network hierarchically regresses the palm pose and the finger pose by information sharing in a multi-task setup. It also uses heat-map guidance to get better feature maps. The experimental re-

sults prove that the proposed strategies are beneficial to get more accurate results, and the results of our method on three 3D hand pose datasets outperform most of previous works. Moreover, the proposed method also achieves the best result in the hand pose estimation challenge, compared to all previous participants. We hope this work can provide a new idea of network design for hand pose estimation.

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