

A Deep Visual Correspondence Embedding Model for Stereo Matching Costs

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Abstract

This paper presents a data-driven matching cost for stereo matching. A novel deep visual correspondence embedding model is trained via Convolutional Neural Network on a large set of stereo images with ground truth disparities. This deep embedding model leverages appearance data to learn visual similarity relationships between corresponding image patches, and explicitly maps intensity values into an embedding feature space to measure pixel dissimilarities. Experimental results on KITTI and Middlebury data sets demonstrate the effectiveness of our model. First, we prove that the new measure of pixel dissimilarity outperforms traditional matching costs. Furthermore, when integrated with a global stereo framework, our method ranks top 3 among all two-frame algorithms on the KITTI benchmark. Finally, cross-validation results show that our model is able to make correct predictions for unseen data which are outside of its labeled training set.

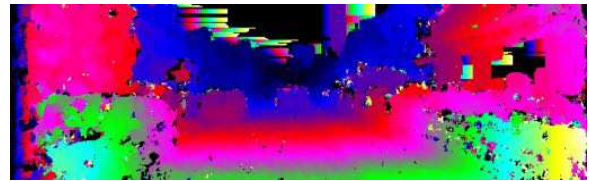
1. Introduction

Stereo matching infers scene geometry by establishing pixel correspondences across multiple images taken from different viewpoints. Scharstein and Szeliski in their seminal taxonomy work [26] argue that stereo algorithms essentially consist of four building blocks: matching cost computation, cost aggregation, disparity computation/optimization and refinement. According to the actual sequence of steps taken, stereo algorithms can be broadly categorized into local and global methods. Local algorithms, where the disparity computation at a pixel depends only on intensity values within a finite support region, usually make implicit

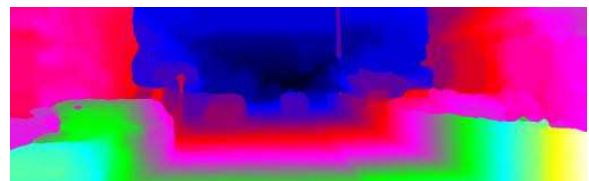
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(a) Reference image of a stereo pair



(b) Winner-takes-all result



(c) Result from an MRF-based stereo framework



(d) color-coded depth

Figure 1. A demonstration of our framework: (a) a left image in the KITTI stereo sequences [13]; (b) we use Convolutional Neural Network to extract discriminative features for stereo matching, which is then refined by a global Markov Random Field to obtain the final result (c). Throughout our paper, we color-code all disparity maps as in (d): blue indicates far regions while white indicates near ones.

smoothness assumptions by aggregating pixel-based matching costs. In contrast, global algorithms typically skip the cost aggregation step by making explicit smoothness

assumptions and seek an optimal disparity assignment by solving an MRF (Markov Random Field) based energy optimization problem.

Matching cost computation, as a fundamental step shared by both local and global stereo algorithms, plays an important role in establishing visual correspondences. Typically, the reconstruction accuracy of a stereo method largely depends on the dissimilarity measurement of image patches. However, the visual correspondence search problem is difficult due to matching ambiguities, which generally results from sensor noise, image sampling, lighting variations, textureless or repetitive regions, occlusions, etc.

In this paper, we focus on the matching cost computation step and present a data-driven approach to address ambiguities. Inspired by the recent advances in deep learning, a new *deep visual correspondence embedding model* is trained via Convolutional Neural Network on a large set of stereo images with ground truth disparities. This deep embedding model leverages appearance data to learn visual dissimilarity between image patches, by explicitly mapping raw intensity into a rich embedding space. Quantitative evaluations with ground truth data demonstrate the effectiveness of our learned deep embedding model for dissimilarity computation. It is first proved that the proposed measure of pixel dissimilarity outperforms some widely used matching costs such as sampling-insensitive absolute differences [1], absolute differences of gradient, normalized cross-correlation and census transform [41] for local window-based matching. Furthermore, we incorporate our learning-based matching costs with a semi-global method (SGM) [16] and show that our model matches state-of-the-art performance on the KITTI stereo data set [13] for accuracy while being superior to other top performers for efficiency and simplicity. Lastly, our deep embedding model is evaluated on the Middlebury benchmark [25] to quantitatively assess its capability of generalization. Cross-validation results show that our model is able to make correct predictions across stereo images outside of its labeled training set.

1.1. Previous Work

Stereo has been a highly active research topic of computer vision for decades and this paper owes a lot to a sizable body of literature on stereo matching, more than we hope to account for here. For the scope of this paper, our focus is on the matching costs computation step and we refer interested readers to [18, 34, 26] for more detailed descriptions and evaluations of different components of stereo algorithms.

Common pixel-based matching costs include absolute differences (AD), squared differences (SD) and sampling-insensitive differences (BT) [1]. In practice, truncated versions of these methods are usually adopted because of

the robustness brought about by the cost aggregation and global optimization steps. Common window-based matching costs include normalized cross-correlation (NCC), sum of absolute or squared differences (SAD/SSD), gradient-based measures, and non-parametric measures such as rank and census transforms [41]. Methods such as BT, SAD and SSD are built strictly on the brightness constancy assumption while gradient-based and non-parametric measures are more robust to radiometric changes (*e.g.*, due to gain and exposure differences) or non-Lambertian surfaces at the cost of lower discriminative power. Recently, self-adapting dissimilarity measures that combine SAD, Census and gradient-based measures are employed by some state-of-the-art stereo algorithms [19, 4, 39].

CNN (Convolutional Neural Networks) dates back decades in the machine learning community [21] and developed rapidly in recent years, thanks to the advances in learning models [23], larger data sets, and parallel computing devices, as well as the access to many online resources [6, 27]. CNN makes breakthroughs in various computer vision tasks such as image classification [20, 32], object detection [14, 10], face recognition [33, 30], and image parsing [11]. Besides its success in high-level vision applications, deep learning also shows its capability in solving certain low-level vision tasks such as super-resolution [7], denoising [2], and single-view depth estimation [8].

Our work is closely related to a recent paper [35], in which CNN is leveraged to compute stereo matching costs. In comparison to [35], our deep embedding model differs from [35] in two main aspects: 1) Given the feature vectors (corresponding to the left right patches in a stereo pair) output by CNN, we directly compute their similarity in the Euclidean space by a dot product. In contrast, the architecture in [35] is more complicated, in that feature vectors requires further fully-connected DNN (Deep Neural Network) to obtain the final similarity score in a non-Euclidean space. The architecture of our CNN leads to two orders of magnitude ($100\times$) speed-up in computing a dense disparity map compared to [35] with little sacrifice in reconstruction accuracy. 2) Our embedding model is learned from a multi-scale ensemble framework, which automatically fuses features vectors learned at different scale-space. Deep learning is also applied in [12, 22] for feature matching. However, [12] extracts features at sparse locations while [22] targets at matching semantically similar regions. Our model is also related to the Deep Flow model [37], where convolutional matching is applied to estimate optical flow. The difference is that [37] applies bottom-up deep dynamic programming on hand-crafted HOG features, while our model is data-driven and learned.

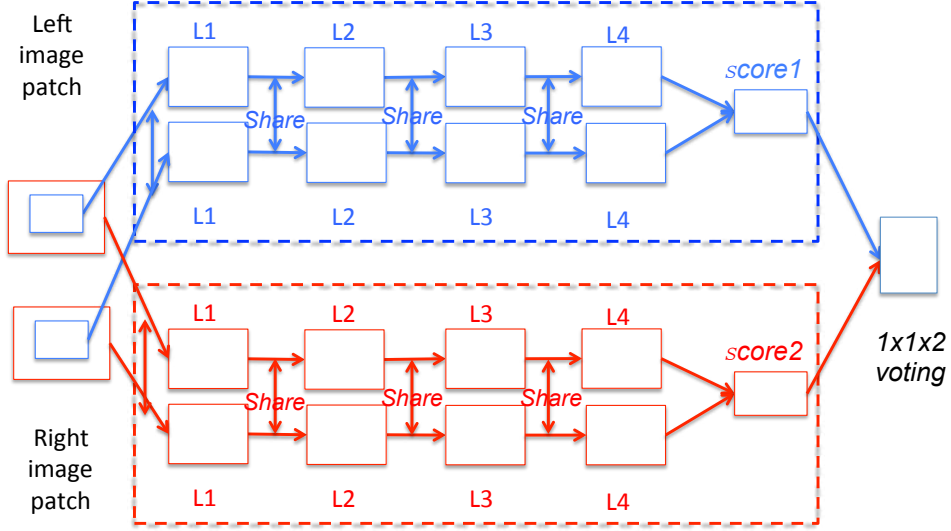


Figure 2. The network architecture of our training model for deep embedding. Features are extracted in a pair of patches at different scales, followed by an inner product to obtain the matching scores. The scores from different scales are then merged for an ensemble.

2. Deep Embedding for Stereo Estimation

Given a pair of rectified left/right images $\{I^L, I^R\}$, a typical stereo algorithm begins by computing the matching quality: denoting patches $I^L(\mathbf{p})$ and $I^R(\mathbf{p} - \mathbf{d})$ centered at $\mathbf{p}^L = (x, y)$ and $\mathbf{p}_d^R = (x - d, y)$, we generate matching score $S(\mathbf{p}, \mathbf{d}) = f(I^L(\mathbf{p}), I^R(\mathbf{p} - \mathbf{d}))$ for each \mathbf{p} with different disparity $\mathbf{d} = (d, 0)$. The score serves as an important initialization, generally followed by a non-local refinement such as cost aggregation or filtering [24, 42]. In this section, we focus on our data-driven model to learn a good matching quality measure.

2.1. Multi-scale Deep Embedding Model

Consider a pair of patches $I^L(\mathbf{p}), I^R(\mathbf{p} - \mathbf{d})$ of size 13×13 , we propose to learn an embedding model to extract features $f(I)$, such that the inner-product $S = \langle f(I^L(\mathbf{p})), f(I^R(\mathbf{p} - \mathbf{d})) \rangle$ tends to be large in case of positive matching and small for negative ones. This differs from the binary classification model in [35].

Multi-Scale Embedding: we apply an ensemble model [11, 5, 8] in our deep embedding, which largely improves the matching quality. Denoting $I_{\downarrow}^L(\mathbf{p}), I_{\downarrow}^R(\mathbf{p} - \mathbf{d})$ as patches at the coarse scale, we have:

$$S(\mathbf{p}, \mathbf{d}) = w_1 \langle f(I^L(\mathbf{p})), f(I^R(\mathbf{p} - \mathbf{d})) \rangle + w_2 \langle f(I_{\downarrow}^L(\mathbf{p})), f(I_{\downarrow}^R(\mathbf{p} - \mathbf{d})) \rangle$$

As we know, the choice of patch scale and size is very tricky: large patches with richer information are less ambiguous, but more risky of containing multiple objects and

producing blurred boundaries; small patches have merits in motion details, but are very noisy. Accordingly, we propose a weighted ensemble of two scales to combine the best of two worlds.

Our embedding framework is shown in Figure 2. The inputs are two pairs of $13 \times 13 \times 1$ image patches, centered at $\mathbf{p} = (x, y)$, $\mathbf{p} - \mathbf{d} = (x - d, y)$ with two different scales. The blue-colored dash box indicates the original resolution while the red is a $\times 2$ down-sampling. We apply a 4-layer CNN model to extract features $f(I)$, followed by an inner-product layer to calculate the matching score $\langle f(I^L), f(I^R) \rangle$ and an ensemble voting. Layer $L1$ and $L2$ contain $c_1 = c_2 = 32$ kernels of size 3×3 ; Layer $L3$ and $L4$ contain kernels $c_3 = c_4 = 200$ of size 5×5 . At both scales, the weights in all layers $L1 \dots L4$ for left and right patches are tied. Then, features $f_4(I) \in R^{200}$ undergo inner-product operations, outputting two scalars $S_1 = \langle f_4(I^L), f_4(I^R) \rangle$ and $S_2 = \langle f_4(I_{\downarrow}^L), f_4(I_{\downarrow}^R) \rangle$ as matching scores. Finally, S_1 and S_2 are merged by a $1 \times 1 \times 2$ convolutional layer for a weighted ensemble.

In our training process, we apply a deep regression model and minimize the Euclidean cost:

$$E(w) = \|S(\mathbf{p}, \mathbf{d}) - label(\mathbf{p}, \mathbf{d})\|^2 \quad (1)$$

where $label(\mathbf{p}, \mathbf{d}) = \{0, 1\}$ indicates whether $\mathbf{p}^L = (x, y)$ corresponds to $\mathbf{p} - \mathbf{d} = (x - d, y)$ in the right image. Rectified linear units [23] follow each layer, but we do not use pooling to preserve spatial-variance.

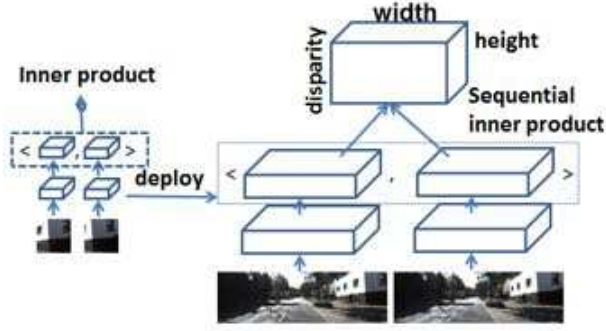


Figure 3. The deployed network architecture of our testing model for deep embedding. Features are extracted in two images **only once** respectively. Then, the sliding-window style inner product can be grouped for **matrix operation**.

2.2. Efficient Embedding for Testing

With deep embedding, we achieve $100\times$ speedup at test time compared to MC-CNN [35]. We attribute this to the largely shared computation in the forward pass as well as grouped matrix operation.

The insight is shown in Figure 3, we extract features $f_4(I)$ in each image **only once** with a fully convolutional neural network, and then the matching score $S(\mathbf{p}, \mathbf{d})$ is computed with all potential offsets \mathbf{d} by the sliding-window style inner product. In comparison, in [35] the fully-connected layers require recomputation every time when d is varied.

Moreover, multiple inner product operations can be **grouped** together as a matrix operation for further acceleration. That is, we multiply $f(I^L(\mathbf{p}))$ with the matrix $F(I^R)$, whose columns contain features $f(I^R(\mathbf{p} - \mathbf{d}))$ with different d . This matrix multiplication is highly parallel in nature.

2.3. Training Details

A training example comprises two pairs of patches $\{I^L(\mathbf{p}), I^R(\mathbf{p} - \mathbf{d})\}$, $\{I^L_{\downarrow}(\mathbf{p}), I^R_{\downarrow}(\mathbf{p} - \mathbf{d})\}$. We sample positive and negative examples at ratio 1 : 1 at each location where the disparity \mathbf{d} is known. A negative example is obtained by shifting the right patch to $\mathbf{p}_d = (x - d + o_{neg}, y)$, where $o_{neg} \in \{-N_{hi}, \dots, -N_{lo}, N_{lo}, \dots, N_{hi}\}$ is a random corrupting offset. Similarly, positive examples are $\mathbf{p}_d = (x - d + o_{pos}, y)$, with $o_{pos} \in \{-P_{hi}, P_{hi}\}$.

In practice, we find that a warm start with large N_{lo} , N_{hi} makes the training converges faster. We gradually decrease N_{lo} , N_{hi} to pursue a hard negative mining.

3. Stereo Framework

To calculate the final disparity map using our proposed matching costs, we adopt an MRF-based stereo framework.

First of all, a cost volume is initialized by negating our deep embedding scores as $C(\mathbf{p}, d) = -S(\mathbf{p}, p_d)$.

Secondly, the initial costs are then fed to the semi-global matcher (SGM) [16, 39] to compute a raw disparity map. Thirdly, after removing unreliable matches via a left-right check, the final disparity map is obtained by propagating reliable disparities to non-reliable areas [29]. In the following, we will briefly summarize the key building blocks in our framework.

Formulating the stereo problem as an MRF model, the SGM aims to find a disparity assignment D that minimizes:

$$E(D) = \sum_p (C(\mathbf{p}, d) + \sum_{q \in N(p)} P_1 [|d - D_q| = 1] + \sum_{q \in N(p)} P_2 [|d - D_q| > 1]) \quad (2)$$

The constant parameters P_1 and P_2 penalize disparity discontinuity and $P_1 < P_2$. While an exact solution to equation (2) is NP-hard, semi-global matcher obtains an approximation by performing multiple dynamic programming (DP)-style $1D$ cost updates along multiple directions as

$$L_{\mathbf{r}}(\mathbf{p}, d) = C(\mathbf{p}, d) + \min(L_{\mathbf{r}}(\mathbf{p} - \mathbf{r}, d), L_{\mathbf{r}}(\mathbf{p} - \mathbf{r}, d \pm 1) + P_1, \min_i (L_{\mathbf{r}}(\mathbf{p} - \mathbf{r}, i) + P_2)) \quad (3)$$

where $L_{\mathbf{r}}(p, d)$ is the cost along a direction \mathbf{r} . After averaging the costs along 16 directions, the initial disparity map is computed for left and right views by picking the disparity hypothesis with the minimal cost.

To efficiently remove the remaining outliers in the initial disparity map, we adopt a propagation scheme [29, 40]. We start by performing a left-right consistency check to roughly divide all pixels into stable and unstable sets. Assuming that a stable pixel \mathbf{p} should satisfy $D^{Left}(\mathbf{p}) = D^{Right}(\mathbf{p} - d)$, we carry out a propagation on the cost volume as:

$$C(\mathbf{p}, d)_{pro} = \begin{cases} |d - D_{Raw}^{Left}(\mathbf{p})|^2 & \mathbf{p} \text{ is stable,} \\ 0 & \text{else.} \end{cases} \quad (4)$$

Here for stable pixels, we penalize disparity deviation from its initial disparity values. In contrast, for unstable pixels, the costs are set to zero for all disparity hypotheses. Thus, an edge-aware filter applied on this cost volume leads to reliable disparity propagation in the cost domain. We choose the $O(1)$ geodesic filter derived from a tree structure [29] due to its effectiveness and efficiency. After filtering the propagated cost volume $C(\mathbf{p}, d)_{pro}$, we again choose the disparity assignment using winner-takes-all. Finally, we employ a 3×3 median filter to remove remaining isolated noises.

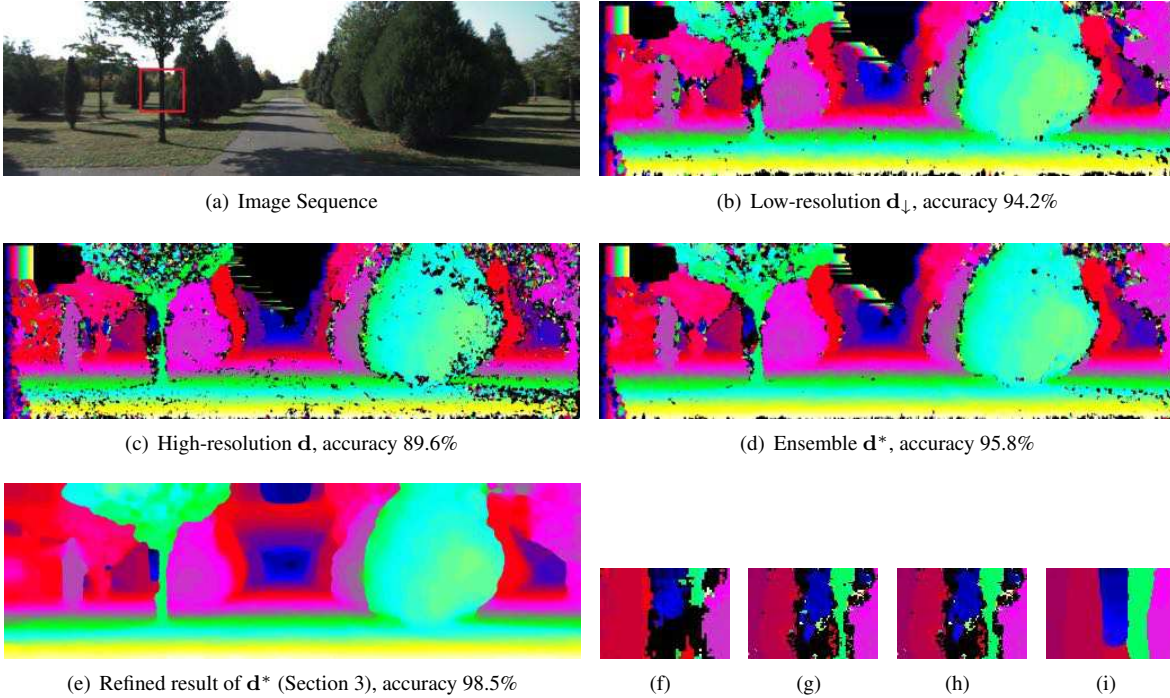


Figure 4. An example of how the proposed multi-scale ensemble works. (a) Frame 10 in KITTI [13]; (b,c) winner-takes-all results of embedding at the coarse and fine scales, respectively; (d) ensemble of (b,c) gives smooth results while preserving details at the same time; (f,g,h,i) are close-up views of (b,c,d,e), respectively.

4. Experimental Results

In this section, we evaluate our algorithm extensively by comparing its performance with other state-of-the-art methods. Our matching costs computation is implemented in CUDA. And the subsequent stereo framework is implemented on a PC equipped with a 3.0 GHz Intel i5 CPU. In our stereo framework, we fix the parameter settings throughout our experiments: $\{P_1, P_2, \sigma_s, \sigma_r\} = \{5, 80, 20, 10.5\}$. Here σ_s and σ_r are the spatial and range kernel parameters used in geodesic filters, respectively.

We use off-the-shelf resource Caffe [6] to train our CNN with a Nvidia GeForce GTX Titan. We optimize the Euclidean loss by a stochastic gradient descent with momentum and weight decay [31]. Specially, we preprocess each image by subtracting the mean and dividing by the standard deviation of its pixel intensity values. It takes about 3 hours to train the CNN with KITTI training set.

4.1. Matching Cost Evaluation

We start by comparing our learning-based matching costs against traditional pixel and window-based matching costs, including BT (Bircheld and Tomasi) [1], census transform [41], AD+Gradient (combination of absolute differences and gradient-based measures), Census+Gradient (combination of census transform and gradient-based measures) [39], and NCC. Among these selected counterparts,

BT and AD+Gradient are popular choices by many competitive stereo algorithms on the Middlebury evaluation system [19, 24]; census transform is reported as the overall best matching cost function in Hirschmuller and Scharstein’s survey [18]; Census+Gradient is used by one of the top performers on the outdoor KITTI data sets [39]; NCC is a classic patch-based measure that is statistically optimal for compensating Gaussian noise [18].

For AD+Gradient and Census+Gradient, we follow the parameter settings as reported in the original literature [19, 39], census transform is computed with a 5×5 local support region. Similar to [18], we use a square window to aggregate the matching costs and calculate the per-pixel disparity value via winner-takes-all. The window size is chosen to be 13×13 because our deep embedding model is learned on the same size. NCC does not go through cost aggregation with the patch width set to 13. Note that no disparity refinement step is applied in this experiment because we want the raw results to provide a more direct assessment of different methods.

We report performance on the 194 KITTI training images in Table 1. As can be seen, our learned matching costs from the deep embedding model substantially outperform traditional matching costs.

Validation of Multi-scale Ensemble: Close scrutiny reveals the complementary power of the embedding results

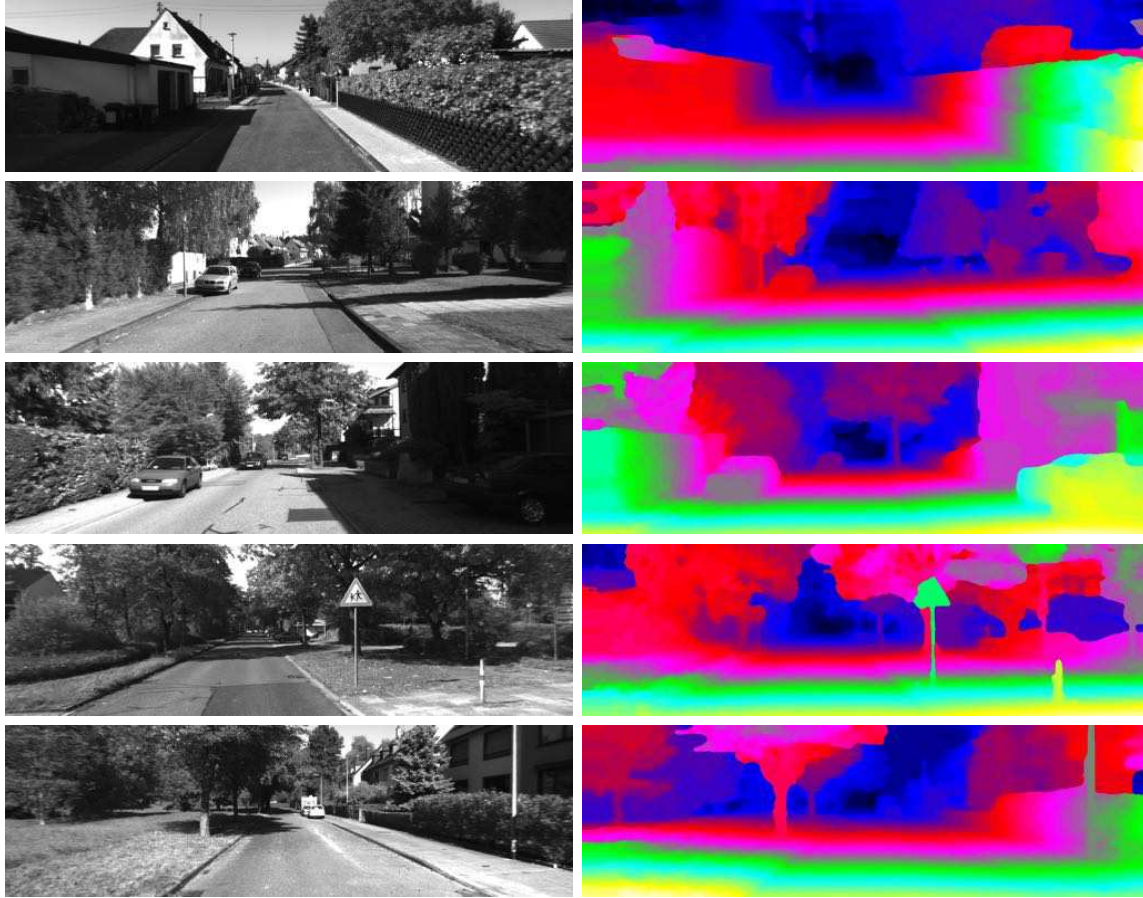


Figure 5. Some disparity map results using our embedding cost on KITTI benchmark. **The left column:** grayscale images of the left frames; **The right column:** our final results. **From top to bottom:** different frames in the KITTI data set.

Methods	All err(%)	Non-occ err(%)
Multi-scale	11.1	9.5
Single-scale (Coarse)	14.8	12.7
Single-scale (Fine)	17.4	14.6
BT	37.8	36.6
Census	25.1	23.4
AD+Gradient	37.4	36.1
Census+Gradient	23.5	21.7
NCC	21.8	19.9

Table 1. Quantitative evaluation of different costs with local-window matching. We compare errors of winner-takes-all results obtained by classical costs with our deep embedding model (single-scale and the multi-scale ensembles) in *all* and *non-occluded* regions.

at different scales (e.g., the 10-th frame in KITTI training set). As shown in Figure 4, the embedding at low-resolution tends to generate more smooth results, but is at risk of losing motion details. Thin structures like the tree marked in box in (a) are missing in (b,f), where the lost mo-

tion proposal can hardly be recovered by post-processing. Meanwhile, noises in high-resolution results (c) can be suppressed by accounting for larger contexts. The accuracy of ensemble (95.8%) is higher than any single scale and a post-processing can produce satisfactory stereo results.

Quantitatively, the average accuracy of winner-takes-all results produced by the fine-scale, coarse-scale and multi-scale ensemble are 85.4%, 87.3% and 90.5% on the KITTI train set, respectively.

4.2. Stereo Pipeline Evaluation

In this section, we incorporate our matching costs with the stereo framework introduced in section 3. The quantitative evaluation results on KITTI test set are shown in table 2, where we compare our model with state-of-the-art methods with only two stereo images for fairness (algorithms that leverage multi-view or temporal/scene flow cues are beyond the scope of this paper). Our method ranks the 3rd among these algorithms in terms of accuracy as of September 2015, and is over an order of magnitude faster than [15] and [35]. Note that replacing our deep embedding costs

Method	Out-Noc	Out-All	Avg-Noc	Avg-All	Runtime	Environment
Displets [15]	2.47 %	3.27 %	0.7 px	0.9 px	265s	8+ cores @ 3.0 Ghz (Matlab + C/C++)
MC-CNN [35]	2.61 %	3.84 %	0.8 px	1.0 px	100s	Nvidia GTX Titan (CUDA, Lua/Torch7)
Ours	3.10 %	4.24 %	0.9 px	1.1 px	3.0s	Nvidia GTX Titan (CUDA, Caffe)
Census+Gradient	3.91 %	5.10 %	0.9 px	1.0 px	2.5s	single core @ 3.0Ghz GPU
CoR[3]	3.30 %	4.10 %	0.8 px	0.9 px	6s	6 cores @ 3.3 Ghz (Matlab + C/C++)
SPS-St[39]	3.39%	4.41%	0.9 px	1.0 px	2s	1 core @3.5 Ghz (C/C++)
DDS-SS[36]	3.83 %	4.59 %	0.9 px	1.0 px	1 min	1 core @ 2.5 Ghz (Matlab + C/C++)
PCBP[38]	4.04 %	5.37 %	0.9 px	1.1 px	5 min	4 cores @ 2.5 Ghz (Matlab + C/C++)
CoR-Conf[3]	4.49 %	5.26 %	1.0 px	1.2 px	6 s	6 cores @ 3.3 Ghz (Matlab + C/C++)
AARBM[9]	4.86 %	5.94 %	1.0 px	1.2 px	0.25 s	1 core @ 3.0 Ghz (C/C++)
wSGM [28]	4.97 %	6.18 %	1.3 px	1.6 px	6s	1 core @ 3.5 Ghz (C/C++)

Table 2. Qualitative evaluation of our pipeline on KITTI benchmark with the error threshold set as 3 pixels. The method "Census+Gradient" uses the same stereo framework, but with Census+Gradient cost function rather than our proposed learning-based matching costs. In terms of runtime, we would like to emphasize that the numbers given in this table are total running time of the whole stereo framework. As reported in the paper [35], the MC-CNN algorithm takes about 95 seconds to compute their learning-based matching costs and 5 seconds for semi-global matching and disparity post-processing steps. In contrast, the running time for our matching cost computation is about 1.0 second, which is around 100 times faster than [35].

with Census+Gradient [39] produces inferior results. A few disparity maps generated by our method are presented in Figure 5, from which we can see that our algorithm produces piecewise smooth and visually plausible results. Our method not only preserves geometry details near depth discontinuities, but also performs well on challenging regions such as textureless and shadow areas.

Regarding the running time, the CNN step takes about 1.0s on average, 734ms at the original resolution and 267ms at the coarse resolution. This is about $100\times$ speedup compared to MC-CNN [35]. The acceleration factor mainly results from fewer model parameters (116,000 versus 600,000 in [35]), fully-convolutional architecture and grouped matrix operation. The not fully optimized MRF stereo implementation takes about 2s on CPU. In total, our approach takes about 3s to process an image at the resolution of 1242×376 with a large disparity searching range from 0 to 255.

4.3. Cross-Validation

It is of interest to evaluate how our model performs on different datasets. Besides KITTI (outdoor street view), we further test our deep embedding model on indoor scenarios without any fine-tuning. We choose stereo sequences from Middlebury benchmarks [25, 17], containing a total number of 27 high resolution image pairs.

Quantitatively, we compare our algorithm with traditional costs such as AD, census transform and NCC. We evaluate the performance with varying error thresholds τ in Figure 6: similar to the setup in section 4.1, we carry out a box aggregation on raw costs and obtain final disparities with a winner-takes-all treatment. It is clear that our embedding model consistently outperforms other methods. Especially, with $\tau = 3$, our method achieves an average er-

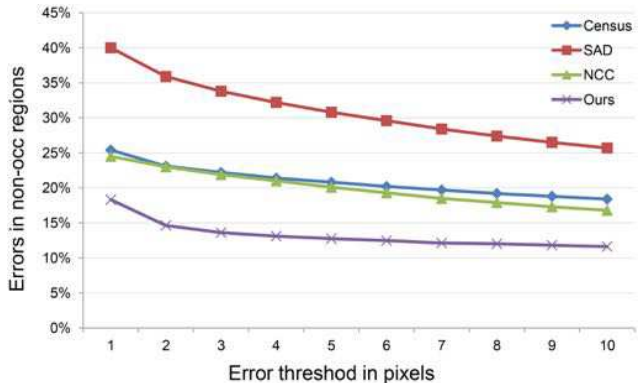


Figure 6. The error curve on Middlebury benchmark with varying error thresholds.

ror rate of 13.6%, which is much lower than SAD (33.8%), census transform (22.2%), and NCC (21.9%). This demonstrates that our deep embedding model generalizes well on scenes that are sufficiently different from the training data. We provide more qualitative results in Figure 7.

5. Conclusion and Future Work

In this paper, we introduce a novel data-driven patch dissimilarity measure for visual correspondence. We learn a deep embedding model to extract discriminative features from patches in stereo pairs. Our model has fewer parameters and shallower network structures therefore is much more efficient than a previous learning-based model [35]. Deep embedding produces high-quality initialization, which can be refined with an MRF-based stereo algorithm to obtain the state-of-the-art dense disparity estimates. Our results on KITTI [13] and Middlebury [26] benchmarks

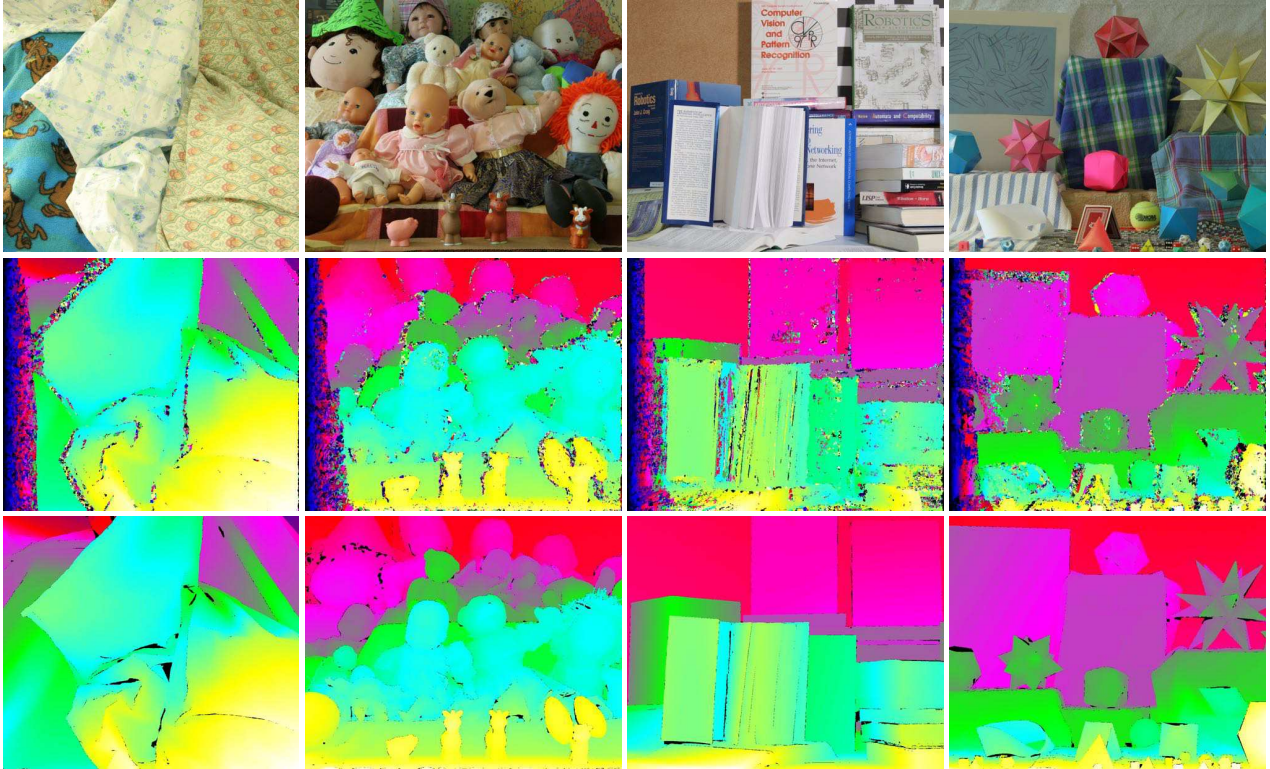


Figure 7. Examples of winner-takes-all results using our deep embedding cost on Middlebury data. **From left to right:** the Cloth, Dolls, Books and Moebius Sequences in Middlebury benchmark; **From top to bottom:** the left images, winner-takes-all results of our deep embedding and ground truth.

suggest that deep embedding is robust across stereo images taken from different environment. In the future, training with larger data sets might have potential to further improve the matching accuracy. We will also accelerate the algorithm for real-time navigation and extend our model to solve other low-level vision problems such as optical flow.

6. Acknowledgements

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References

- [1] S. Birchfield and C. Tomasi. A pixel dissimilarity measure that is insensitive to image sampling. *PAMI*, 20:401–406, 1998.
- [2] H. C. Burger, C. J. Schuler, and S. Harmeling. Image denoising: Can plain neural networks compete with bm3d? *CVPR*, pages 2392–2399, 2012.
- [3] A. Chakrabarti, Y. Xiong, S. J. Gortler, and T. Zickler. Low-level vision by consensus in a spatial hierarchy of regions. *CVPR*, 2015.
- [4] Z. Chen, H. Jin, Z. Lin, S. Cohen, and Y. Wu. Large displacement optical flow from nearest neighbor fields. *CVPR*, 2013.
- [5] D. Ciresan, U. Meier, and J. Schmidhuber. Multi-column deep neural networks for image classification. *CVPR*, pages 3642–3649, 2012.
- [6] J. Donahue, Y. Jia, O. Vinyals, J. Hoffman, N. Zhang, E. Tzeng, and T. Darrell. Decaf: A deep convolutional activation feature for generic visual recognition. *ICML*, 2014.
- [7] C. Dong, C. C. Loy, K. He, and X. Tang. Learning a deep convolutional network for image super-resolution. *ECCV*, 2014.
- [8] D. Eigen, C. Puhrsch, and R. Fergus. Depth map prediction from a single image using a multi-scale deep network. *NIPS*, pages 2366–2374, 2014.
- [9] N. Einecke and J. Eggert. Block-matching stereo with relaxed fronto-parallel assumption. In *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*, pages 700–705, 2014.
- [10] D. Erhan, C. Szegedy, A. Toshev, and D. Anguelov. Scalable object detection using deep neural networks. *CVPR*, 2014.
- [11] C. Farabet, C. Couprie, L. Najman, and Y. LeCun. Learning hierarchical features for scene labeling. *PAMI*, 35(8):1915–1929, 2013.
- [12] P. Fischer, A. Dosovitskiy, and T. Brox. Descriptor matching with convolutional neural networks: a comparison to sift. *Technical Report 1405.5769, arXiv(1405.5769)*, 2014.

- [13] A. Geiger, P. Lenz, and R. Urtasun. Are we ready for autonomous driving? the kitti vision benchmark suite. In *CVPR*, 2012.
- [14] R. Girshick, J. Donahue, T. Darrell, and J. Malik. Rich feature hierarchies for accurate object detection and semantic segmentation. *CVPR*, 2014.
- [15] F. Güney and A. Geiger. Displets: Resolving stereo ambiguities using object knowledge. In *CVPR*, 2015.
- [16] H. Hirschmüller. Stereo processing by semiglobal matching and mutual information. *PAMI*, 30(2):328–341, 2008.
- [17] H. Hirschmüller and D. Scharstein. Evaluation of cost functions for stereo matching. *CVPR*, 2007.
- [18] H. Hirschmüller and D. Scharstein. Evaluation of stereo matching costs on images with radiometric differences. *PAMI*, 31:1582–1599, 2009.
- [19] A. Klaus, M. Sormann, and K. Karner. Segment-based stereo matching using belief propagation and a self-adapting dissimilarity measure. *ICPR*, 2006.
- [20] A. Krizhevsky, I. Sutskever, and G. E. Hinton. Imagenet classification with deep convolutional neural networks. *NIPS*, 2012.
- [21] Y. LeCun, L. Bottou, Y. Bengio, and P. Haffner. Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, 86(11):2278–2324, 1998.
- [22] J. Long, N. Zhang, and T. Darrell. Do convnets learn correspondence? *NIPS*, 2014.
- [23] V. Nair and G. E. Hinton. Rectified linear units improve restricted boltzmann machines. *ICML*, 2010.
- [24] C. Rhemann, A. Hosni, M. Bleyer, C. Rother, and M. Gelautz. Fast cost-volume filtering for visual correspondence and beyond. In *CVPR*, 2011.
- [25] D. Scharstein and C. Pal. Learning conditional random fields for stereo. *CVPR*, 2007.
- [26] D. Scharstein and R. Szeliski. A taxonomy and evaluation of dense two-frame stereo correspondence algorithms. *IJCV*, 47(1-3):7–42, 2002.
- [27] P. Sermanet, D. Eigen, X. Zhang, M. Mathieu, R. Fergus, and Y. LeCun. Overfeat: Integrated recognition, localization and detection using convolutional networks. *arXiv preprint arXiv:1312.6229*, 2013.
- [28] R. Spangenberg, T. Langner, and R. Rojas. Weighted semi-global matching and center-symmetric census transform for robust driver assistance. In *In Computer Analysis of Images and Patterns*, pages 34–41, 2013.
- [29] X. Sun, X. Mei, S. Jiao, M. Zhou, Z. Liu, and H. Wang. Real-time local stereo via edge-aware disparity propagation. *PRL*, 49:201–206, 2014.
- [30] Y. Sun, X. Wang, and X. Tang. Deep learning face representation from predicting 10,000 classes. *CVPR*, 2014.
- [31] I. Sutskever, J. Martens, G. Dahl, and G. Hinton. On the importance of initialization and momentum in deep learning. *ICML*, 2013.
- [32] C. Szegedy, W. Liu, Y. Jia, P. Sermanet, S. Reed, D. Anguelov, D. Erhan, V. Vanhoucke, and A. Rabinovich. Going deeper with convolutions. *arXiv:1409.4842*, 2014.
- [33] Y. Taigman, M. Yang, M. Ranzato, and L. Wolf. Deepface: Closing the gap to human-level performance in face verification. *CVPR*, 2014.
- [34] F. Tombari, S. Mattoccia, L. D. Stefano, and E. Addimanda. Classification and evaluation of cost aggregation methods for stereo correspondence. *CVPR*, 2008.
- [35] J. Žbontar and Y. LeCun. Computing the stereo matching cost with a convolutional neural network, 2014.
- [36] D. Wei, C. Liu, and W. T. Freeman. A data-driven regularization model for stereo and flow. In *3D Vision (3DV), 2014 2nd International Conference on*, 1:277–284, 2014.
- [37] P. Weinzaepfel, J. Revaud, Z. Harchaoui, and C. Schmid. Deepflow: Large displacement optical flow with deep matching. *ICCV*, pages 1385–1392, 2013.
- [38] K. Yamaguchi, T. Hazan, D. McAllester, and R. Urtasun. Continuous markov random fields for robust stereo estimation. In *ECCV*, pages 45–58, 2012.
- [39] K. Yamaguchi, D. McAllester, and R. Urtasun. Efficient joint segmentation, occlusion labeling, stereo and flow estimation. *ECCV*, 2013.
- [40] Q. Yang. A non-local cost aggregation method for stereo matching. In *CVPR*, 2012.
- [41] R. Zabih and J. Woodfill. Non-parametric local transforms for computing visual correspondence. *ECCV*, 1994.
- [42] K. Zhang, J. Lu, and G. Lafuit. Cross-based local stereo matching using orthogonal integral images. *IEEE Transactions on Circuits and Systems for Video Technology*, 19(7):1073–1079, 2009.