Spatial-Temporal Space Hand-in-Hand:  
Spatial-Temporal Video Super-Resolution via Cycle-Projected Mutual Learning

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Abstract

Spatial-Temporal Video Super-Resolution (ST-VSR) aims to generate super-resolved videos with higher resolution (HR) and higher frame rate (HFR). Quite intuitively, pioneering two-stage based methods complete ST-VSR by directly combining two sub-tasks: Spatial Video Super-Resolution (S-VSR) and Temporal Video Super-Resolution (T-VSR) but ignore the reciprocal relations among them. Specifically, 1) T-VSR to S-VSR: temporal correlations help accurate spatial detail representation with more clues; 2) S-VSR to T-VSR: abundant spatial information contributes to the refinement of temporal prediction. To this end, we propose a one-stage based Cycle-projected Mutual learning network (CycMu-Net) for ST-VSR, which makes full use of spatial-temporal correlations via the mutual learning between S-VSR and T-VSR. Specifically, we propose to exploit the mutual information among them via iterative up-and-down projections, where the spatial and temporal features are fully fused and distilled, helping the high-quality video reconstruction. Besides extensive experiments on benchmark datasets, we also compare our proposed CycMu-Net with S-VSR and T-VSR tasks, demonstrating that our method significantly outperforms state-of-the-art methods. Codes are publicly available at: \url{https://github.com/hhhhhumengshun/CycMuNet}.

1. Introduction

Spatial-temporal video super-resolution (ST-VSR) aims to produce the high-resolution (HR) and high-frame-rate (HFR) video sequences from the given low-resolution (LR) and low-frame-rate (LFR) input. This task has drawn great attention due to its popular applications \cite{29,30,53}, including HR slow-motion generation, movie production, high-definition television upgrades, \textit{etc}. Great success has been recently achieved in ST-VSR tasks, as illustrated in Figure 1(a), which can be roughly divided into two categories: two-stage and one-stage based methods. The former decomposes it into two sequential sub-tasks: spatial video super-resolution (S-VSR) and temporal video super-resolution (T-VSR), which are individually completed with image/video super-resolution technologies \cite{19,51,58} and video frame interpolation technologies \cite{28,40}. However, more spatial information generated by the S-VSR task can be used for the refinement of temporal prediction, while more temporal information predicted by the T-VSR task can be used to facilitate the reconstruction of spatial details. As a result, the two-stage based approaches are far from producing satisfied predictions due to lacking the ability to mutually explore the coupled correlations between S-VSR and T-VSR.

Recently, integrating these two sub-tasks into a unified framework with a one-stage process becomes more popular. Naturally, based on the parallel or serially processing modes (Figure 1(b) (i) for parallel process and (ii)(iii) for serial process), diverse and effective schemes have been developed \cite{7,8,29,30,53,55}. Unfortunately, the parallel methods \cite{29,30} barely consider the coupled correlations between the two sub-tasks, while the serial methods \cite{53,55} fail to fully exploit mutual relations since they only focus on the unilateral relationship, such as “T-to-S” or “S-to-T”. In particular, the unilateral learning will accumulate reconstruction errors, which we define as cross-space (spatial and temporal spaces) errors, consequently leading to obvious aliasing effect in super-resolved results.

For thorough utilization of spatial and temporal information, we propose to promote the one-stage method with mutual learning, and devise a novel cycle-projected mutual learning network (CycMu-Net) for ST-VSR. As shown in Figure 1(c), the philosophy of CycMu-Net is to explore the mutual relations and achieve the spatial-temporal fusion to eliminate the cross-space errors. Specifically, the key part of CycMu-Net is the iterative up-and-down projection units between the spatial and temporal embedding spaces, involv-
Figure 1. Different schemes for ST-VSR. (a) Two-stage based methods: (i) they perform ST-VSR task by independently using the advanced S-VSR methods and then T-VSR methods or vice versa (ii). (b) One-stage based method: they unify S-VSR and T-VSR tasks into one model with parallel or cascaded manners without considering the mutual relations between S-VSR and T-VSR. (c) Mutual method: Our method makes full use of the mutual relations via mutual learning between S-VSR and T-VSR.
For example, Shechtman et al. adopt a directional spatial-temporal smoothness regularization to constrain high spatial-temporal resolution video reconstruction [43]. Mudenagudi et al. [36] formulate their ST-VSR method as a posteriori-Markov Random Field [17] and optimize it by achieving the Maximum of graph-cuts [5]. However, the above methods cost great computational consumption and fail to model complex spatial-temporal correlations. Recently, learning-based methods attempt to unify S-VSR and T-VSR into a single-stage framework for ST-VSR. Kim et al. utilize a multi-scale U-net to learn ST-VSR based on a multi-scale spatial-temporal loss [30]. Haris et al. propose to explore spatial-temporal correlations by a pre-trained optical flow model for frame interpolation and refinement [22]. Xiang et al. devise a unified framework to interpolate intermediate features by deformable convolution [51], explored global temporal correlations by bidirectional deformable ConvLSTM [54], and finally reconstructed high spatial-temporal videos by a reconstruction network [53]. Inspired by [53], Xu et al. introduce a locally temporal feature comparison module to extract local motion cues in videos, achieving better performance on various datasets [55]. However, as shown in Figure 1(b), the mutual relations between S-VSR and T-VSR are under-explored, while leading to the accumulated reconstruction errors. To address this issue, we propose a cycle-projected mutual learning network that learns the spatial-temporal correlations via the iterative operation of spatial and temporal fusion (S-VSR and T-VSR) during the forward propagation and backward optimization.

2.4. Mutual Learning

Mutual learning is to make a pool of untrained students to learn collaboratively and teach each other for solving the task [59]. Dual-NMT utilizes mutual learning to teach two cross-lingual translation models each other interactively machine translation [23]. Tanmay Batra et al. propose to learn multiple models jointly and communicate object attributes each other for recognising the same set of object categories [4]. Dong et al. adopted this tool to exploit non-adjacent features for image dehazing by fusing features from different levels [15]. The closest thing to our work is DBPN [19], which proposes utilize mutually iterative up- and down-sampling layers to learn nonlinear relationships between LR and HR images to guide the image SR task. Previous studies have validated the effectiveness of mutual learning techniques for low-level tasks [14,16,21,60]. However, the existing methods tend to exploit the mutual learning to refine the mapping relations of different scale spaces (“LR-to-HR” and “HR-to-LR”). Inspired by them, we introduce a novel cycle-projected mutual learning mechanism to cooperatively characterise the spatial and temporal feature representations.

3. Cycle-Projected Mutual Learning Network

In this section, we first provide an overview of the proposed Cycle-projected Mutual learning network (CycMu-Net) for ST-VSR. As shown in Figure 2, given two LR input frames $L_0$ and $L_1$, our goal is to synthesize HR intermediate frame $H_t$ and the corresponding HR input frames $H_0$ and $H_1$ ($2\times$, $4\times$, or $8\times$). In addition, we also generate a LR frame $L_t$ as an intermediate result. The proposed CycMu-Net first extracts the representation from the input frames by a feature extractor (FE). To synthesize the initialized LR intermediate representation, we introduce a cascading multi-scale architecture as our feature temporal interpolation network (FTI-Net), designed to learn bi-directional motion offsets to handle complex motions and interpolate intermediate representation by deformable convolution. To make full use of the mutual relations (“T-to-S” or “S-to-T”)
between S-VSR and T-VSR, we adopt mutual learning that temporal correlations contribute to accurate spatial representations and updated spatial predictions refine temporal information via feedback, to eliminate the cross-space errors, which can be achieved via iterative up-projection units (UPUs) and down-projection units (DPUs). After several iterations, we obtain multiple HR and LR representations and then concatenate them into the reconstruction network (R) to generate the corresponding HR images $H_0$, $H_t$ and $H_1$ ($2 \times 4 \times$, or $8 \times$) and LR image $L_t$.

3.1. Cycle-Projected Mutual Learning

Inspired by [19] that adequately addressed the mutual dependencies of low- and high-resolution images via mutually connected up- and down-sampling layers, in this paper, we propose a new mutual learning model including iterative UPUs and DPUs to explore the mutual relations between S-VSR and T-VSR. In particular, temporal correlations provide more clues to compensate detailed spatial representation via UPUs while abundant spatial details are used to refine the temporal predictions via DPUs.

As shown in the top of Figure 3, the UPU captures temporal correlations for S-VSR. We firstly project previous LR temporal representations $l_{m-1}^0$, $l_{m-1}^t$ and $l_{m-1}^1$ to corresponding HR representations $u_{m-1}^0$, $u_{m-1}^t$ and $u_{m-1}^1$ based on a scale up module, which can be described as follows:

$$[u_{m-1}^0, u_{m-1}^t, u_{m-1}^1] = UP_0([l_{m-1}^0, l_{m-1}^t, l_{m-1}^1]),$$

where $UP_0(\cdot)$ denotes the scale up module. It first performs multi-frame progressive fusion by fusion resblocks [57], which implicitly exploit intra-frame spatial correlations and inter-frame temporal correlations, then upsamples each feature by bilinear interpolation and $1 \times 1$ convolution. $m = 1, 2, ..., M$ denotes the number of UPU.

Then we try to project the super-resolved representations back to LR representations and compute the corresponding residuals (errors) $e_{0}^{m-1}$, $e_{t}^{m-1}$ and $e_{1}^{m-1}$ between back-projected representations and original LR representations, respectively, which can be defined as follows:

$$[e_{0}^{m-1}, e_{t}^{m-1}, e_{1}^{m-1}] = DN([u_{m-1}^0, u_{m-1}^t, u_{m-1}^1]) - [l_{0}^{m-1}, l_{t}^{m-1}, l_{1}^{m-1}],$$

where $DN(\cdot)$ denotes the scale down module. It first reduces the input to the original input resolution via $4 \times 4$ convolution with stride 2, and then further implicitly explores intra-frame spatial correlations and inter-frame temporal correlations of LR representations by fusion resblocks [57].

Finally, we project residual representations again back to HR representations (back-project) and eliminate the corresponding original super-resolved representations errors (cross-space errors) to obtain the final super-resolution outputs of the unit by

$$[h_{0}^{m}, h_{t}^{m}, h_{1}^{m}] = UP_1([e_{0}^{m-1}, e_{t}^{m-1}, e_{1}^{m-1}]),$$

where $UP_1(\cdot)$ denotes the scale up module.

As shown in the bottom of Figure 3, the procedure for DPU is very similar, while its main role is to obtain refined LR temporal representations by projecting the previously updated HR representations, which can provide abundant spatial details. (Please refer to the supplementary materials for more details about formula proof, scale up module and scale down module)

3.2. Spatial-Temporal Video Super-Resolution

The overall framework of CycMu-Net is shown in Figure 2, consisting of the following sub-modules: feature extraction network, feature temporal interpolation network, multiple up-projection units, multiple down-projection units, and reconstruction network. Specifically, we extract representations among multiple frames via feature extraction network (FE) and interpolate the intermediate representations via the feature temporal interpolation network (FTI-Net). Then we use the proposed multiple UPUs and DPUs to obtain multiple LR and HR representations with the mutual learning. Finally, the reconstruction network (R) generates LR intermediate frame and HR intermediate frames by concatenating all LR and HR representations. Below we describe the details of each sub-module.

**Feature temporal interpolation network.** Deformable convolution [13, 61] has been shown to be effective for video frame interpolation [10] and video super-resolution [49]. Some methods extended deformable convolution and explored a wider range of offsets by employing a multi-scale framework to handle feature alignment for small and large displacements [51, 53, 55]. Inspired by them, we utilize a cascading multi-scale architecture for our feature
temporal interpolation network (FTI-Net) to estimate the bi-directional motion offsets from input frames. Along with the motion offsets estimation, we adopt deformable convolution to interpolate forward and backward representations from the missing intermediate frames. To blend these two representations for obtaining an initial intermediate representation, we use the two learnable convolution kernels to estimate the weights, which can adaptively fuse the two representations according to their importance. (More details on FTI-Net are provided in the supplementary materials)

Reconstruction network. After the mutual relations between S-VSR and T-VSR are exploited by the proposed iterative up-and-down projections, we concatenate and feed multiple HR representations into convolution layers to reconstruct the corresponding HR frames. In addition, we also reconstruct a LR intermediate frame based on multiple LR representations. To optimize the whole CycMu-Net, we use a reconstruction loss function:

\[
L_r = \lambda_1 \rho(L_t - L_t^{GT}) + \lambda_2 \rho(H_t - H_t^{GT}) + \lambda_3 \rho(H_0 - H_0^{GT}) + \lambda_4 \rho(H_1 - H_1^{GT}),
\]

where \(L_t^{GT}, H_0^{GT}, H_1^{GT}\) and \(H_r^{GT}\) refer to the corresponding ground-truth video frames. \(\rho(x) = \sqrt{x^2 + \omega^2}\) is the Charbonnier penalty function \([9, 32]\). We set the constant \(\omega\) and weights \(\lambda_1, \lambda_2, \lambda_3\) and \(\lambda_4\) to \(10^{-5}, 1, 1, 0.5\) and \(0.5\), respectively.

3.3. Implementation Details

We implement the proposed CycMu-Net using Pytorch 1.9 with four NVIDIA 2080Ti and optimize the model using AdaMax optimizer \([31]\) with a momentum of 0.9. The batch size is set to 10 with image resolution of \(64\times 64\). The initial learning rate is set to \(4\times10^{-4}\) and reduced by a factor of 10 every 20 epochs for a total of 70 epochs. We compare HR intermediate frame \(H_t\) for the evaluation of ST-VSR. In addition, we also compare our proposed CycMu-Net with S-VSR and T-VSR methods, where \(4\times\) HR frame \(H_0\) and LR intermediate frame \(L_t\) are used for the evaluations of S-VSR and T-VSR, respectively.

4. Experimental Results

4.1. Datasets and Metrics

Vimeo90k \([56]\). We use Vimeo90K dataset to train our proposed CycMu-Net. This dataset consists of many triplets with different scenes from 14,777 video clips with image resolution of \(448\times256\). Among them, 51,312 triplets and 3,782 triplets are used for training and testing, respectively. In order to increase the diversity of data, we use horizontal and vertical flipping or reverse the order of input frames for data augmentation. For a fair comparison with other algorithms during training, we downscale to original images to \(64\times64\) with Bicubic interpolation for \(2\times\) and \(4\times\) SR, and downscaled to original images to \(32\times32\) with Bicubic interpolation for \(8\times\) SR.

UCF101 \([45]\). The UCF101 dataset consists of videos with a large variety of human actions. There are 379 triplets with the resolution of \(256\times256\) for testing. The original images are sampled to \(32\times32, 64\times64\) and \(128\times128\) with Bicubic for \(8\times, 4\times\) and \(2\times\) SR tasks in testing.

Middlebury [1]. The Middlebury dataset is widely used to evaluate video frame interpolation algorithms [2, 10]. Here, we select Other set which provides the ground-truth middle frames, only to test our method on T-VSR task. The image resolution in this dataset is around \(640\times480\) pixels.

Metric. We use Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM) \([52]\) and the average Interpolation Error (IE) for performance evaluation. The higher PSNR and SSIM and lower IE values indicate better super-resolution and interpolation performance.

4.2. Comparisons with State-of-the-Art Methods

ST-VSR. We compare our CycMu-Net with state-of-the-art two-stage and one-stage based ST-VSR methods. For the two-stage based ST-VSR methods, SepConv \([40]\), AdaCoF \([33]\) and CAIN \([12]\) are introduced for T-VSR task, while Bicubic Interpolation, RBPN \([20]\), DBPN \([19]\) and EDVR \([51]\) are used for S-VSR. For one-stage based ST-VSR methods, we compare our CycMu-Net with Zooming SlowMo \([53]\), STARnet \([22]\) and TMNet \([55]\). For fair comparison, three triplets from Vimeo90K dataset are used to retrain SlowMo and TMNet methods.

Quantitative results. Quantitative results are presented in Table 1. We can see that besides fewer parameters, one-stage based methods show significant superiority than the two-stage based methods in all metrics. In particular, the best two-stage based method (SepConv+RBPN) is 0.66dB lower than our method for \(8\times\) VSR on Vimeo90K dataset. Furthermore, compared to the state-of-the-art one-stage based methods, our proposed CycMu-Net outperforms STARNet \([22]\), Zooming Slow-Mo \([53]\) and TMNet \([55]\) on all datasets with all metrics, while with only one-tenth of parameters to STARNet. All these results validate the effectiveness of our proposed method for ST-VSR task.

Qualitative results. The qualitative results of seven ST-VSR baselines with their PSNR and SSIM values are shown in Figure 4. As expected, two-stage based ST-VSR methods tend to produce blurry results (see the yellow boxes) since they ignore the mutual relations between S-VSR and T-VSR, which help the accurate texture inference. Compared to two-stage based methods, one-stage based ST-VSR methods can generate complete results. However, these methods ignore that S-VSR provides abundant spatial information for the refinement of temporal prediction, leading to the generated results without more texture information.
Table 1. Quantitative comparisons (×2, ×4, ×8 from left to right) of the state-of-the-art methods for ST-VSR. The numbers in red and blue represent the best and second best performance.

<table>
<thead>
<tr>
<th>Methods</th>
<th>UCF101</th>
<th>Vimeo90K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PSNR</td>
<td>SSIM</td>
</tr>
<tr>
<td>Bicubic</td>
<td>29.988</td>
<td>0.944</td>
</tr>
<tr>
<td>DBPN [19]</td>
<td>32.041</td>
<td>0.958</td>
</tr>
<tr>
<td>RBPN [20]</td>
<td>31.889</td>
<td>0.957</td>
</tr>
<tr>
<td>EDVR [51]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>AdaCoF [33]</td>
<td>30.056</td>
<td>0.945</td>
</tr>
<tr>
<td>AdaCoF [33] + DBPN [20]</td>
<td>31.216</td>
<td>0.957</td>
</tr>
<tr>
<td>AdaCoF [33] + EDVR [51]</td>
<td>31.997</td>
<td>0.958</td>
</tr>
<tr>
<td>AdaCoF [33] + EDVR [51]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CAIN [12]</td>
<td>29.931</td>
<td>0.941</td>
</tr>
<tr>
<td>STARNet [22]</td>
<td>32.200</td>
<td>0.959</td>
</tr>
<tr>
<td>Zooming Slow-Mo [53]</td>
<td>32.211</td>
<td>0.960</td>
</tr>
<tr>
<td>CycMu-Net</td>
<td>32.258</td>
<td>0.960</td>
</tr>
</tbody>
</table>

Figure 4. Visual comparisons (8×) with state-of-the-art methods on Vimeo90K dataset.

Table 2. Quantitative comparisons of the state-of-the-art methods for S-VSR (H0) on UCF101 and Vimeo90K datasets.

<table>
<thead>
<tr>
<th>Methods</th>
<th>UCF101</th>
<th>Vimeo90K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PSNR</td>
<td>SSIM</td>
</tr>
<tr>
<td>Bicubic</td>
<td>27.254</td>
<td>0.889</td>
</tr>
<tr>
<td>DBPN [19]</td>
<td>30.898</td>
<td>0.938</td>
</tr>
<tr>
<td>RBPN [20]</td>
<td>31.309</td>
<td>0.943</td>
</tr>
<tr>
<td>EDVR [51]</td>
<td>31.452</td>
<td>0.944</td>
</tr>
<tr>
<td>CycMu-Net</td>
<td>31.463</td>
<td>0.944</td>
</tr>
</tbody>
</table>

S-VSR. We compare the proposed network with image SR methods including Bicubic and DBPN [19], and S-VSR methods including RBPN [20] and EDVR [51]. The results on S-VSR are shown in Table 2, showing that S-VSR methods (EDVR [51] and RBPN [20]) can achieve superior performance than image SR methods (bicubic and DBPN [19]) by referring to multiple frames for temporal correlations. In addition, we can see that our CycMu-Net has comparable results with EDVR, but it requires only half of the parameters of EDVR and three triplets rather than seven frames for training. This also validates the powerful generalization ability of our network, and our proposed up-projection units are helpful for S-VSR tasks by exploiting temporal correlations from T-VSR.

T-VSR. We compare our proposed network with state-of-the-art T-VSR which include SpeConv-[40], SepConv-[40], AdaCoF-[33], CAIN-[12], STARnet-[22], and TMNet-[55]. The results from T-VSR are shown in Table 2, showing that S-VSR methods (EDVR [51] and RBPN [20]) can achieve superior performance than image SR methods (bicubic and DBPN [19]) by referring to multiple frames for temporal correlations. In addition, we can see that our CycMu-Net has comparable results with EDVR, but it requires only half of the parameters of EDVR and three triplets rather than seven frames for training. This also validates the powerful generalization ability of our network, and our proposed up-projection units are helpful for S-VSR tasks by exploiting temporal correlations from T-VSR.
Figure 5. Visual comparisons of temporal video super-resolution on Middlebury dataset.

Figure 6. Visual comparisons (4×) of four variants for the ablation studies on Vimeo90K dataset.

Table 3. Quantitative comparisons of the state-of-the-art methods for T-VSR ($L_1$).

Table 4. Quantitative comparisons on the performance (4×) of different modules.

4.3. Model Analysis

Ablation Study. To further verify the key modules in CycMu-Net, comprehensive ablation studies are conducted for 4× SR.

Model (a): A fusion feature interpolation (FFT) network is used to direct fuse input information from input frames and produce intermediate representation without motion estimation. Then two pixel-shuffle layers take the representations as inputs, and produce the 4× SR video with a convolution.

Model (b): We add deformable convolution as implicit motion estimation into feature interpolation network (FTI-Net) in Model (a) as our deformable feature interpolation (DFI) network, as stated in section 3.2.

Model (c): Based on Model (b), we add addition iterative plain-projection units (PP) without up-down sampling between the feature temporal interpolation network and reconstruction network.

Model (d): The complete version of CycMu-Net.

The visual and numerical comparisons are shown in Figure 6 and Table 4. Compared to Model (a) that produces the intermediate representations without motion estimation, the results of Model (b) show that adopting deformable convo-
The accurate inference errors. Extensive experiments demonstrate our proposed method performs well against the state-of-the-art methods in both S-VSR, T-VSR and ST-VSR tasks. While achieving impressive performance, one limitation of this study is that since videos might contain dramatically changing scenes, the spatial-temporal correlations of large motion or SR factors is hardly predicted via the iterative up-projection and down-projection units. One reasonable scheme is to alleviate the learning burden by dividing it into multiple sub-tasks with small motion, which is helpful for accurate texture inference.

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### 5. Conclusion

In this work, we propose a novel one-stage based Cycle-projected Mutual learning network (CycMu-Net) for spatial-temporal video super-resolution. Theoretically, we introduce mutual learning to explore the interactions between spatial video super-resolution (S-VSR) and temporal video super-resolution (T-VSR), from which the abundant spatial information and temporal correlations are aggregated to infer accurate intermediate frame. Specifically, an elaborate iterative representation between up-projection units and down-projection units is introduced to make full use of the spatial-temporal features while eliminating the inference errors. Extensive experiments demonstrate our proposed method performs well against the state-of-the-art methods in both S-VSR, T-VSR and ST-VSR tasks. While achieving impressive performance, one limitation of this study is that since videos might contain dramatically changing scenes, the spatial-temporal correlations of large motion or SR factors is hardly predicted via the iterative up-projection and down-projection units. One reasonable scheme is to alleviate the learning burden by dividing it into multiple sub-tasks with small motion, which is helpful for accurate texture inference.
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