Ink Enhancement for Ancient Bamboo Manuscripts Using Iterative Restoration-Degradation Adversarial Learning

Chongsheng Zhang   Junchao Ma   Wenhao Zhang   Kamel Aouaidjia   Qilong Li
Gaojuan Fan   Christian Heumann

Abstract

Bamboo Slips are precious manuscripts, but suffer from ink fading problem, which seriously impacts their legibility. We propose BambInk, which is a new self-supervised learning method for ink enhancement over Bamboo Slips. It devises an iterative restoration-degradation adversarial learning mechanism to progressively enhance the faded inks on the Bamboo Slips, yet without requiring any annotated data. In specific, BambInk designs two generators which are ink enhancer and ink degrader, and two discriminators for evaluating the effects of the enhanced and degraded images, respectively. Experiments conducted on real-world dataset demonstrate the effectiveness of our method. Code, data and enhanced results are available at: https://github.com/cszhangLMU/BambInk.

Main Contributions

- This work is among the first technical initiatives that investigate ink enhancement over ancient Bamboo Slips with faded inks.
- It designs a self-supervised iterative restoration-degradation adversarial learning method to progressively enhance texts with faded inks on the Bamboo Slips, yet without requiring any annotated data.

Methodology

BambInk is a self-supervised iterative adversarial learning framework for ink enhancement over degraded Bamboo Slips. Inspired by CycleGAN, it consists of four key components: an ink enhancer ($\mathrm{G_{en}}$) and an ink degrader ($\mathrm{G_{de}}$); and an enhancement effect discriminator ($\mathrm{D_{en}}$) and a degradation effect discriminator ($\mathrm{D_{de}}$). BambInk does not require any annotated data in its training, because for $\mathrm{D_{en}}$ and $\mathrm{D_{de}}$, it only needs to separately pick ink-legible and ink-faded bamboo slip images for training each of the two discriminators, respectively.

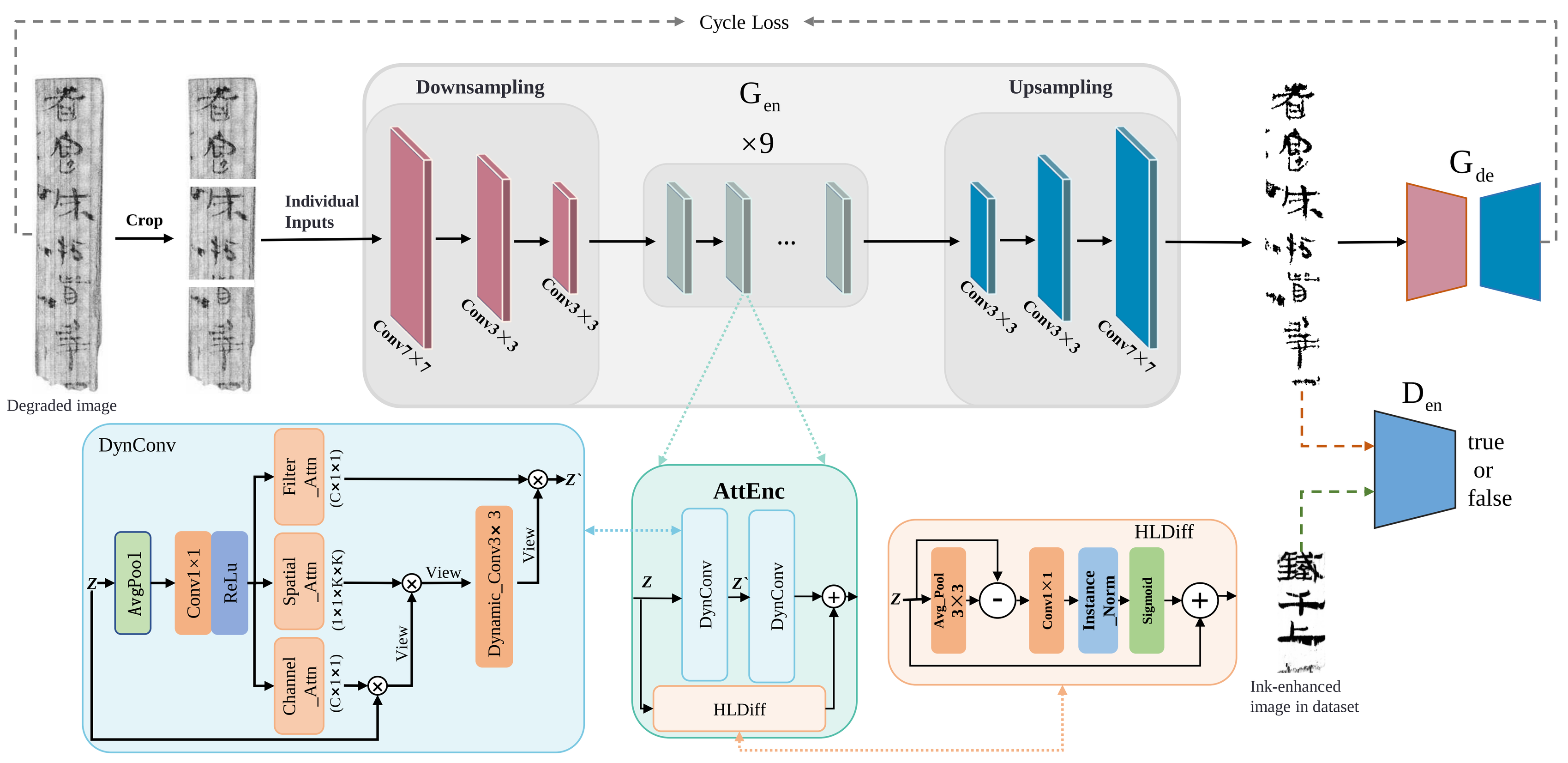

Figure 1. Detailed architecture for the ink enhancer $\mathrm{G_{en}}$ in BambInk, which is a self-supervised iterative adversarial learning framework for ink enhancement.

Detailed architecture of the ink enhancer $\mathrm{G_{en}}$ in BambInk is depicted in Figure 1, which is an encoder-decoder framework with special bottle encoder AttEnc to pay attention to the ink strokes in the image. In specific, AttEnc integrates different types of features captured using three types of attention: spatial attention, channel attention, and filter attention to extract both global and local stroke features for better ink traces preservation; it also devises a simple yet effective high- and low-frequency information differentiation mechanism for extracting the fine-details of the ink traces. Finally, the corresponding discriminator $\mathrm{D_{en}}$ for $\mathrm{G_{en}}$ aims to discriminate between the generated ink-enhanced images from $\mathrm{G_{en}}$ and real-world images with clear ink traces.

Note that, the detailed architecture of $\mathrm{G_{de}}$ is omitted in Figure 1, which mirrors the architecture of $\mathrm{G_{en}}$ in the opposite direction, aiming to turn ink-enhanced images into degraded images. The corresponding discriminator $\mathrm{D_{de}}$ aims to discriminate between the degraded images and the original images.

During the training phase, the total loss of the model is composed of contributions from the ink enhancer $\mathrm{G_{en}}$, the ink degrader $\mathrm{G_{de}}$, the enhancement discriminator $\mathrm{D_{en}}$, and the degradation discriminator $\mathrm{D_{de}}$. The generators' losses are defined as follows:

$$L_{G_{\mathrm{en}}} = L_{\mathrm{adv}}\left(G_{\mathrm{en}}, D_{\mathrm{en}}\right) + \lambda_{\mathrm{cyc}} L_{\mathrm{cyc}}\left(G_{\mathrm{en}}, G_{\mathrm{de}}\right) + \lambda_{\mathrm{id}} L_{\mathrm{id}}\left(G_{\mathrm{en}}\right) \tag{1}$$

$$L_{G_{\mathrm{de}}} = L_{\mathrm{adv}}\left(G_{\mathrm{de}}, D_{\mathrm{de}}\right) + \lambda_{\mathrm{cyc}} L_{\mathrm{cyc}}\left(G_{\mathrm{en}}, G_{\mathrm{de}}\right) + \lambda_{\mathrm{id}} L_{\mathrm{id}}\left(G_{\mathrm{de}}\right) \tag{2}$$

where L_{adv} denotes the adversarial loss, and L_{cyc} represents the cycle-consistency loss. Meanwhile, $L_{\mathrm{id}}\left(G_{\mathrm{en}}\right)$ and $L_{\mathrm{id}}\left(G_{\mathrm{de}}\right)$ correspond to the identity losses on the G_{en} and G_{de}, respectively. The discriminators' losses are defined as follows:

$$L_{D_{\mathrm{en}}} = \frac{1}{2}\mathrm{E}_{y\sim Y}\left[\left(D_{\mathrm{en}}(y)-1\right)^2\right] + \frac{1}{2}\mathrm{E}_{x\sim X}\left[D_{\mathrm{en}}(G_{\mathrm{en}}(x))^2\right] \tag{3}$$

$$L_{D_{\mathrm{de}}} = \frac{1}{2}\mathrm{E}_{x\sim X}\left[\left(D_{\mathrm{de}}(x)-1\right)^2\right] + \frac{1}{2}\mathrm{E}_{y\sim Y}\left[D_{\mathrm{de}}(G_{\mathrm{de}}(y))^2\right] \tag{4}$$

Experiments

We conduct experiments on a subset of *Xuanquan* Bamboo Slips. We select 350 images from the ink-legible Xuanquan II Bamboo Slips as samples of the target domain and randomly choose 400 images from the degraded Xuanquan I Bamboo Slips as the degraded source domain.

Unsupervised Evaluation. In the unsupervised evaluation, we compare the enhanced images with the original input images using three metrics: the Frechet Inception Distance (FID), Kernel Inception Distance (KID), and Structural Similarity Index Measure (SSIM), to assess the effectiveness of the enhanced images in terms of distribution matching and overall structural integrity. As demonstrated in Table 1, BambInk achieves the best performance on FID, KID, and SSIM scores. In specific, on the FID metric, BambInk is 71.0 lower than Niblack (181.2), which reflects stronger distribution consistency; on the KID metric, it is 0.055 lower than WAN (0.095), which shows more accurate feature mapping; and on the SSIM metric, it shows 0.251 higher than ZigZag (0.601), indicating superior structural detail preservation capabilities.

Methods	FID↓	KID↓	SSIM↑
Ostu	244.3	0.170	0.561
NiBlack	181.2	0.100	0.361
Sauvola	235.4	0.166	0.596
Wolf	189.7	0.106	0.568
Gatos	347.4	0.327	0.575
Su	350.8	0.333	0.589
ISauvola	337.2	0.315	0.573
WAN	185.8	0.095	0.519
AutoFoc	324.5	0.278	0.565
ZigZag	285.8	0.229	0.601
CycleGAN	134.9	0.060	0.802
BambInk (Ours)	**110.2**	**0.040**	**0.852**

Table 1. Comparison with other methods on unsupervised evaluation metrics.

Supervised Evaluation–Binarization. We make pixel-level annotations for 100 degraded Bamboo Slips, which will be used as the ground-truth (GT) in binarization. We calculate the F-Measure (FM), Pseudo F-Measure (pFM), Peak Signal-to-Noise Ratio (PSNR), and Distortion Ratio Difference (DRD) scores to quantitatively measure the ink-enhancement effects. In Table 2, we see that BambInk improves over CycleGAN on the four metrics by 2.10, 1.70, 0.67, and 2.46, respectively. This demonstrates the efficacy of BambInk in ink enhancement for degraded Bamboo Slips.

Methods	FM↑	pFM↑	PSNR↑	DRD↓
Ostu	60.32	59.97	10.11	41.64
NiBlack	32.96	32.94	4.62	125.3
Sauvola	65.77	65.16	11.27	23.59
Wolf	57.62	57.41	9.50	36.36
Gatos	70.06	69.22	12.25	18.55
Su	68.32	67.57	12.79	*15.39*
ISauvola	68.20	67.45	11.81	20.52
WAN	49.22	49.12	7.85	55.96
AutoFoc	66.80	66.06	12.71	18.52
ZigZag	*71.86*	*70.80*	*12.94*	15.78
CycleGAN	76.81	75.24	14.11	11.02
BambInk(Ours)	**78.91**	**76.94**	**14.78**	**8.56**

Table 2. Comparison with other methods on supervised evaluation metrics.

Figure 2 presents the visual comparison results with different methods on two input Bamboo slip images.

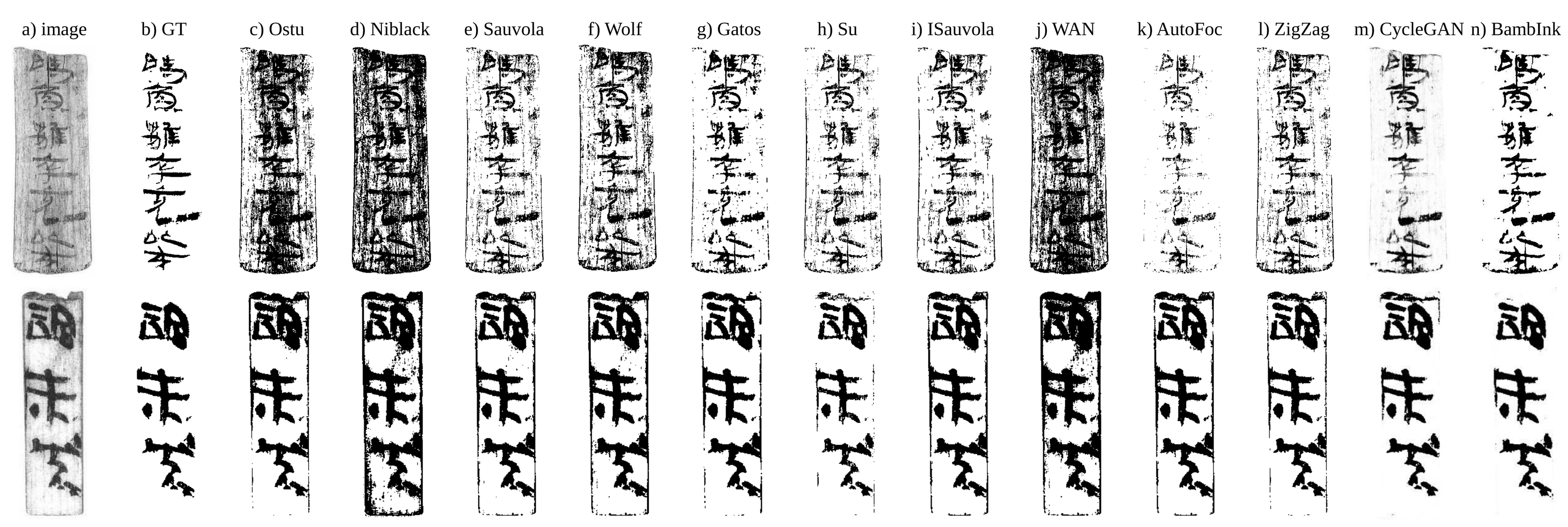

Figure 2. Visual comparisons with different methods.

Conclusions

In this work, we investigate ink enhancement on degraded ancient Bamboo Slips. We proposed BambInk, a self-supervised framework using iterative restoration-degradation adversarial learning. It consists of an ink enhancer and an ink degrader as generators and two associated discriminators to evaluate each generators' performance. We carry out unsupervised image-quality based evaluations and binarization based supervised evaluations to comprehensively assess the ink enhancement effects of BambInk. In future research, we will develop more advanced ink enhancement methods for degraded Bamboo Slips.