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Attention for Image Registration (AiR): an unsupervised Transformer approach

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Abstract. Image registration as an important basis in signal processing task often encounter the problem of stability and efficiency. Non-learning registration approaches rely on the optimization of the similarity metrics between the fix and moving images. Yet, those approaches are usually costly in both time and space complexity. The problem can be worse when the size of the image is large or the deformations between the images are severe. Recently, deep learning, or precisely saying, the convolutional neural network (CNN) based image registration methods have been widely investigated in the research community and show promising effectiveness to overcome the weakness of non-learning based methods. To explore the advanced learning approaches in image registration problem for solving practical issues, we present in this paper a method of introducing attention mechanism in deformable image registration problem. The proposed approach is based on learning the deformation field with a Transformer framework (AiR) that does not rely on the CNN but can be efficiently trained on GPGPU devices also. In a more vivid interpretation: we treat the image registration problem as the same as a language translation task and introducing a Transformer to tackle the problem. Our method learns an unsupervised generated deformation map and is tested on two benchmark datasets. The source code of the AiR will be released at Gitlab.³

Keywords: Transformer · Images Registration · Deep Learning

1 Introduction

In many areas such as remote sensing, radar engineering and medical imaging, the problem of matching two images for further processing (eg: images synthesis, stitching or segmentation etc.) is a basic but popular research topic [1–3]. This task is named image registration which can be divided into rigid and non-rigid registration. The deformable images registration is one of the difficult branches of image registration as the finding of the deformation field between the images to be matched is a highly nonlinear problem. Traditional approaches rely on the

³ <https://gitlab.inria.fr/zihwang/transformer-for-image-registration>

collection of images features and using different similarity metrics to measure the matching quality between images pairs during the optimization [4].

With the rapid promotion of deep learning in the field of medical image analysis, various variant of convolutional neural networks (CNN) are introduced for image registration and obtained eye-catching results in many research works. Wu *et al.* [5] introduced the CNN for automatic feature extraction to replace the manual feature extraction during registration. Cao *et al.* [6] proposed to learn the non-linear mapping between the input images and the deformation fields with a meticulously designed CNN architecture where the training dataset is prepared with a diffeomorphic demons based registration dataset. De vos *et al.* [7] used an unsupervised Deep Learning Image Registration (DLIR) that using CNN to regress the mapping between the images pairs and the deformation map. The framework is unsupervised as the output of CNN is used directly for warping the moving images to generate the deformed images with transposed convolutions which allow the backpropagate for the resampling operation. Krebs *et al.* [8] proposed to learn a probabilistic deformation model based on variational inference of a conditional variational auto-encoder (CVAE) which maps the deformations representation in a latent space. The trained CVAE can be used to generate deformations for an unseen image.

Since the Transformers based learning models were proposed, it has rapidly expanded from the field of natural language processing (NLP) to the entire machine learning community [9–11]. As a very successful application of attention conception, the Transformer already conquered the NLP regime and almost replaced the traditional widely-used RNN/LSTM models. The recent advance of Transformers application in image/videos analysis implies that the Transformer have the potential power to show off in structure data processing. The Transformer is a different learning model which does not need convolutional kernels for features representation but learns the data inherent relationships through the **attention mechanism** [12]. Recent works in the computer vision community report that the Transformer based deep learning methods achieved state-of-the-art performance on many datasets. As a representative work that introduces the Transformer in computer vision, the vision Transformer (ViT) was proposed by [13] for image classification. The ViT takes the divided patches p_i of a given image I as the inputs (see Fig. 1 step (a)) and using a Transformer as the attention features extractor to generate features for classification. Another work that using a Transformer for object detection is the DETR [14]. The DETR accepts the image and the detection objects for the Transformer as the inputs and generates the corresponding bounding box information of the target objects on the images. Recent state-of-the-art performance of Transformer for multi-task are achieved by Swin Transformer [15]. The Swin Transformer uses a similar hierarchical structure for building the different attention perception field size on the target images.

In this paper, we propose a novel unsupervised **attention mechanism** based image registration (AiR) framework. This paper serves as an attempt to introduce the Transformer model into the field of image registration. Unlike the previ-

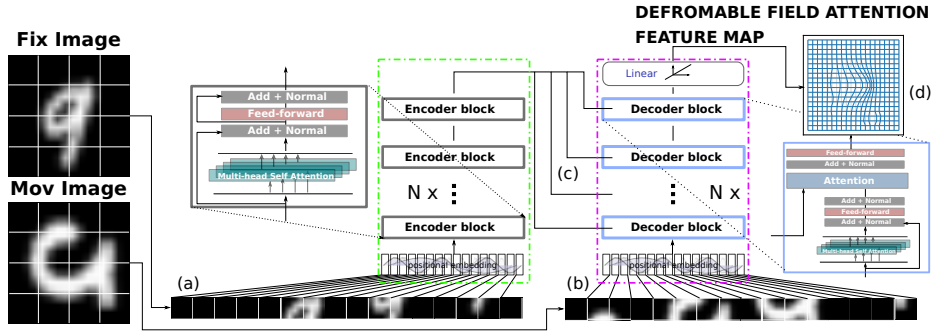


Fig. 1. The transformer framework used for deformation attention feature map prediction. The proposed transformer consists of encoder and decoder modules. The encoder module (shown in the green dotted line box) takes the fixed images patches as input and learns the representation of the memory attention features with self-attention mechanism. The decoder module (shown in the purple dotted line box) takes the attention features of the fixed image from the encoder (memory) and the self-attentions features of the moving image as input for predicting the deformable features that can transform the moving image into a fixed image.

our CNN based method, our method framework using a Transformer for learning the deformation information between fix and moving images without convolution operation. In addition, unlike many prior works of using a Transformer in the computer vision community, the proposed framework does not rely on any neural network backbone as a prior feature extractor. To the best of our knowledge, the proposed framework is the first Transformer based image registration method. The proposed Transformer based image registration framework is an unsupervised registration framework that the training deformation fields are not necessary. In addition, we proposed a multi-scale attention parallel Transformer framework for better solving incompetent cross-level feature representation of conventional Transformer.

2 Method

2.1 Attention for Image Registration (AiR)

The proposed attention-based image registration framework is based on the Transformer model [12]. The transformer model can be treated as a dimensional isotropic projection:

$$T_{\theta} : T(x) \rightarrow z; x, z \in \mathbb{R}^{n \times d} \quad (1)$$

where T is the projection which parameterized by a set of parameters $\theta : \{W_q, W_k, W_h, W_c, W_r\}$. The computational pipeline start from the input tensor

x to output tensor z is given through:

$$\begin{aligned}
 Query &= W_q \cdot x; Key = W_k \cdot x; Value = W_v \cdot x; \\
 \alpha &= softmax(\langle Query, Key \rangle / \sqrt{k}); \\
 z' &= \sum_{h=1}^H W_c \sum_{j=1}^J \alpha \cdot Value; \\
 z &= NormRelu(z')
 \end{aligned} \tag{2}$$

In our problem setting, we want the Transformer to learn the deformation map between two images, thus the prediction target tensor z is the corresponding deformation map for warping the moving image to the fixed image. The usual way of CNN based methods is merging the fix and moving images in channel dimension as input for regression the relationship between the deformation maps and input images pairs. In our framework, we treat the image registration problem as an image translation problem that similar to using the Transformer in the NLP task. In detail, we want the Transformer to learn the deformation map (attention features) that can translate the moving image (foreign language) into the fixed image (native language). Based on this idea, we introduce the encoder-decoder Transformer framework for image registration by using the encoder to model the fixed image and using the decoder for modelling the moving image. The self-attention maps that come from the fixed image are injected into the attention blocks of the decoder. The final output attention map of the Transformer is used for warping the moving image to match the fixed image.

To feed the images to Transformer the images need to be processed as sequence data-points [13]. To this end, the fixed I_f and moving I_m images pairs are firstly divided into $i \cdot i$ (see in Fig .1 step (a) where $i = 4$) patches and then embedded by linear projection with added position embedding to get the position information.

The fixed image patches are fed to transformer encoder network which encoding the attention features of the fixed images. The transformer encoder network contains N recursive blocks as shown in the green box of Fig. 1. Simultaneously, the moving images patches are fed together with the output attention features to the transformer decoder network (step (c) in Fig. 1). The output of the Transformer decoder network is processed with a linear projection layer to generate the deformation attention feature maps.

Similar to the DLIR [7], the generated deformation features is then processed by a spatial Transformer (STN) layer [16] for generating the displacement field to sample the moving images. As shown in Fig. 2, the output of the STN layer is then used for sampling the moving image to generate the warped image. In the end, the backpropagation is achieved by optimizing the similarity metric that measures the similarity between the deformed images and the fixed images.

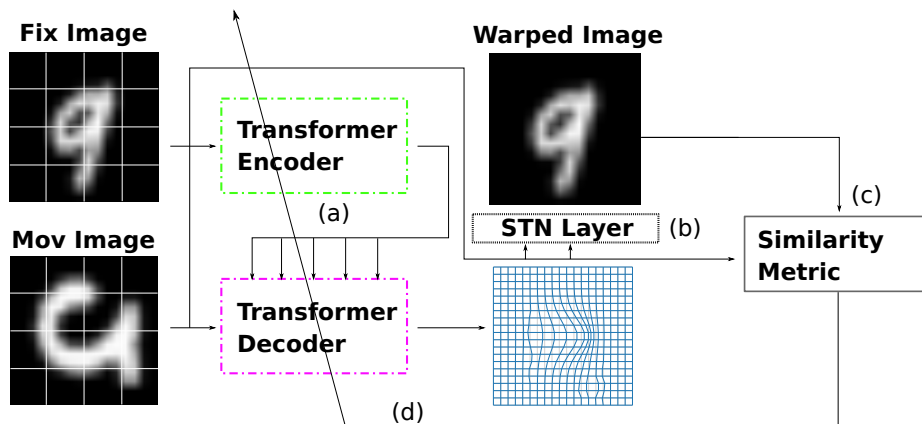


Fig. 2. The Transformer based image registration framework. In step (a): The input images are converted to deformation feature maps by the Transformer. In step (b): Those feature maps are converted to deformation field for a sampler to warp the moving image. Steps (c) -(d): The warped moving image is quantified by the similarity metric for computing the gradients flow for back-propagation.

3 Multi-scale Parallel Attention Transformer

The CNN based method can use feature layer hierarchical superposition and different size of convolutional kernels for features expression in different levels. Yet, as the transformer is not a convolutional based method, the ability of cross feature level feature extraction is comparatively weaker. This problem can be observed also in our experimental section for a single level Transformer (patch size equal to 2) based AiR framework.

To get the multi-level feature learning for Transformer, we propose a Multi-scale Attention Parallel Transformer (MAPT) that can learn the features from different perception scales. The MAPT consists N Transformers (N decoders and N encoders). For each transformer, they adapt the different size of patches as inputs and generates N different attention feature maps F_N . The N feature maps are then sampled into a uniform size for adding together with normalized weighting ratio to get the final deformable feature map F .

4 Experiments and Evaluation

4.1 Dataset and Experiment Details

We evaluate the multi and single scale Transformer based AiR frameworks in comparison with the CNN based DIRNets on the MNIST dataset and Fashion-MNIST [17, 18]. During the training period, the randomly picked pairs are used to feed the AiR transformer for gradients decent. We use 20% of data for testing the performance of the AiR Transformer and 80% of images for training. The

Transformer in our experiment contains 1 block ($N = 1$) for both the Transformer encoder and decoder networks. The dropout ratio of the encoder and decoder layers is set as 0.5. The attention layers of the Transformer consist of 4 heads for both the multi-head self-attention and attention layers. The projection dimension was set as 16 for both the encoder and decoder networks. We train all the frameworks with an Adam optimization with learning rate: $lr = 0.5e - 3$. All of the experiments were run on an Asus ESC8000 GPU node with two Xeon SP Gold 5115 @ 2.4 GHz CPU and using one GeForce GTX 1080 Ti GPU. The program was implemented with the Pytorch framework.

4.2 Results and Evaluation

Fig. 3 shows the registration results of different approaches. We see from the generated results that all the frameworks can learn the warping mapping between the moving image and the fixed images. However, different algorithms perform differently in terms of deformation qualities.

In the upper row of Fig. 3 we use DIRNets which is a CNN based registration framework to register the random paired data sampled from Fasion-MNIST dataset. We see that some of the deformation maps are over or under deformed for DIRNets results. The results obtained from MAPT-AiR framework can capture globally shape deformations as the target images shapes are well-matched, while the MAPT-AiR still fails in details portrayal in comparison with the CNN based method. The under lower of Fig. 3 shows the registration performance comparison between Single-AiR and MAPT-AiR. Both the algorithms show qualitatively reasonable performances. Yet, we see that the Single-AiR framework may fail for large deformations matching for example the number 4, 9. In contrast, the MAPT-AiR can be modeling the large deformations with better quality (eg. number 9, 7, 8).

Overall, we observe from the figure that for transformer based registration methods, although the overall shape of the sampled images is similar to the fixed images, there are defects and noises in geometric details for the warped images. This defect may be related to the quality of the generated deformable fields. Many recent works have pointed out that the transformer is more inferior to CNN in terms of pixel-level details processing ability [19] [20]. This problem is also observed in our experiment.

Table 1. Quantitative comparison between different methods on MNIST handwriting dataset.

	Original Image	DIRNets	AiR-Single Attention	AiR-Parallel Attention
MSE	0.0647±0.029	0.033±0.014	0.038±0.015	0.027±0.015
PSNR	12.941±2.218	16.966±2.897	15.65±2.638	17.311±2.522
Smooth DICE	0.756±0.039	0.809±0.033	0.797±0.032	0.827±0.034

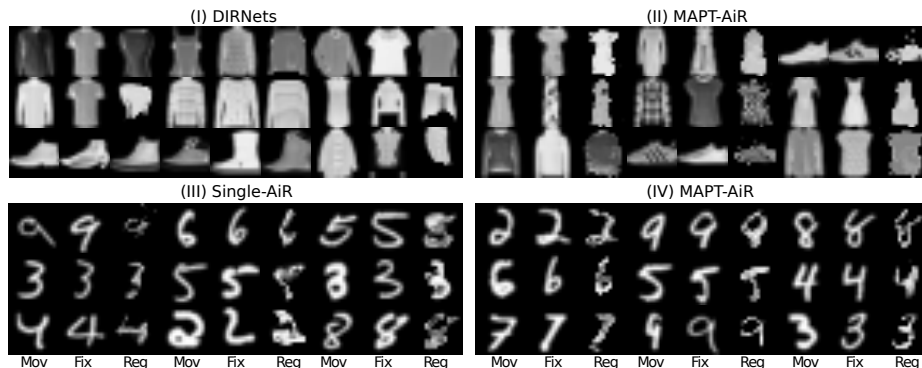


Fig. 3. Registration results of different approaches on different datasets: (I) CNN based method performance on Fashion-MNIST dataset. (II) Multi-scale Parallel Attention Transformer (MPAT) based AiR results on Fashion-MNIST dataset. (III) Single Transformer based AiR on MNIST dataset. (IV) MPAT based AiR results on the MNIST dataset.

We quantitatively study the performance of different frameworks with three different metrics in Tab. 1. The multi-scale attention based Transformer framework achieves the best index crossing those three different frameworks. We see that using only a single attention Transformer is not better than the CNN based registration framework. This is expected as the single scale Transformer can not learn the features crossing different scale levels, while the crossing level modeling ability is a strong power of CNN. Yet, as shown in the Tab. 1, this problem can be solved by using the multi-scale attention framework.

5 Conclusion

In this work, we presented an Attention mechanism-based Image Registration framework: AiR. The framework was built based on the Transformer model which is different from current commonly used CNN based approaches. We have shown in the experiment section that the proposed framework can achieve the goal of unsupervised deformable images registration. The results show that the Transformer model can achieve plausible performance for image registration. However, as the Transformer is a young research topic in computer vision, there are still many limitations for wide application compared to current CNN-based methods. A typical problem is the current Transformer is GPU-bound which leads to the prohibition for conventional computing systems. There is still a lot of work to be done to deal with the computational complexity for the current Transformer framework.

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