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# SSM-NET: FEATURE LEARNING FOR MUSIC STRUCTURE ANALYSIS USING A SELF-SIMILARITY-MATRIX BASED LOSS

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## ABSTRACT

In this paper, we propose a new paradigm to learn audio features for Music Structure Analysis (MSA). We train a deep encoder to learn features such that the Self-Similarity-Matrix (SSM) resulting from those approximates a ground-truth SSM. This is done by minimizing a loss between both SSMs. Since this loss is differentiable w.r.t. its input features we can train the encoder in a straightforward way. We successfully demonstrate the use of this training paradigm using the Area Under the Curve ROC (AUC) on the RWC-Pop dataset.

## 1. INTRODUCTION

Music Structure Analysis (MSA) is the task aiming at identifying musical segments that compose a music track (a.k.a. segment boundary estimation) and possibly label them based on their similarity (a.k.a. segment labeling). Over the years, systems for MSA have switched from

- hand-crafted detection system (checker-board-kernel [1] or DTW [2]) applied to hand-crafted audio features (MFCC or Chroma)
- to deep learning detection system (boundary detection using ConvNet [3–5]) applied to hand-crafted audio features, and recently
- to hand-crafted detection system (checker-board-kernel) applied to deep learned features [6, 7].

Among the paradigms used to learn these features, metric learning using the triplet loss [8] has been the most popular, either using unsupervised learning [6] or using supervised learning [7]. In this paper, we propose a new paradigm to learn these features, which is more straightforward and less-computationally expensive (on a GPU Tesla P100-PCIE, training in about 1 hour for our approach and 24 hours for [6]).

## 2. PROPOSAL: SSM-NET

Our SSM-net system is illustrated in Figure 1. The inputs and architecture (but not the loss) of our system are in-

spired by McCallum’s work [6] (but largely simplified<sup>1</sup>).

**Input data**  $\{\mathbf{X}_i\}$ . Each audio track is represented as a temporal sequence of  $T$  audio features  $\mathbf{X}_i$  which we denote as  $\{\mathbf{X}_i\}_{i \in \{1 \dots T\}}$  or  $\{\mathbf{X}_i\}$  for short.  $\{\mathbf{X}_i\}$  are beat-synchronized patches of Constant-Q-Transform (CQT), each centered on a beat position  $b_i$ <sup>2</sup>. Each patch represents 4 successive beats<sup>3</sup>. Each beat is further sub-divided into 16 sub-beats. For this, the content of the CQTs between two successive beats  $b_{i-1}$  and  $b_i$  is analyzed and clustered<sup>4</sup> into 16. The inputs to our network are therefore patches  $\mathbf{X}_i$  of CQT, each of size (72 frequencies, 4\*16 sub-beats) and centered on a beat  $b_i$ .

**Network architecture**  $\mathbf{e}_i^\theta = f^\theta(\mathbf{X}_i)$ . The architecture of our encoder  $f^\theta$  is illustrated in Figure 1. It comprises 3 consecutive blocks (L1, L2, L3) of a 2D convolution followed by a SELU [12] activation, a 2D group normalization [13] with 32 channels and a 2D max-pooling, The convolutional layers use a kernel size of (f=6, t=4)<sup>5</sup> and the max-pooling layers use respectively kernel sizes of (2, 4), (3, 4) and (3, 2). The output is then passed to a single Fully-Connected (FC) layer of 128 units with a SELU activation. The output is then L2-normalized and constitutes the embedding  $\mathbf{e}_i^\theta = f^\theta(\mathbf{X}_i)$ .  $\theta$  denotes the set of parameters to be trained (348.400 parameters). For comparison the original McCallum [6] network has 1.280.768.

**SSM-Net Loss.** We apply the same encoder  $f^\theta$  to each input  $\mathbf{X}_i$ . We then obtain the corresponding sequence of embeddings  $\{\mathbf{e}_i^\theta\}_{i \in \{1 \dots T\}} = f^\theta(\{\mathbf{X}_i\}_{i \in \{1 \dots T\}})$ . We can then easily construct an estimated SSM,  $\hat{\mathbf{S}}_{ij}^\theta$ , using a distance/similarity  $g$  function between all pairs of projections:

$$\hat{\mathbf{S}}_{ij}^\theta = g(\mathbf{e}_i^\theta = f^\theta(\mathbf{X}_i), \mathbf{e}_j^\theta = f^\theta(\mathbf{X}_j)), \quad \forall i, j \quad (1)$$

$g$  is here a simple cosine-similarity which we scale to  $[0, 1]$ :

$$\hat{\mathbf{S}}_{ij}^\theta = 1 - \frac{1}{4} \|\mathbf{e}_i^\theta - \mathbf{e}_j^\theta\|_2^2 \in [0, 1] \quad (2)$$

It is then possible to compare  $\hat{\mathbf{S}}_{ij}^\theta$  to a ground-truth binary SSM,  $\mathbf{S}_{ij}$ . We formulate this as a multi-class problem

<sup>1</sup> We reduced the sampling rate of the features by a factor 8: McCallum divides each beat into 128 sub-beats while we only use 16 sub-beats. We divided by a factor 2 the number of convolutional filters of each layer and we removed the last two fully connected layers.

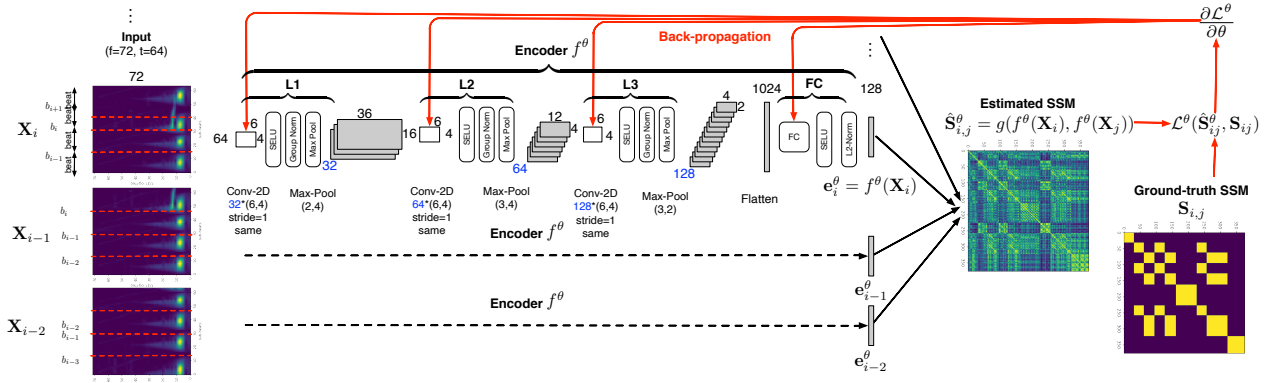
<sup>2</sup> The CQTs are computed using `librosa` [9]. We used 72 log-frequencies ranging from C1 (31.70 Hz) to C7 (2093 Hz).

<sup>3</sup> The beat positions  $\{b_i\}$  are computed using `madmom` [10] [11].

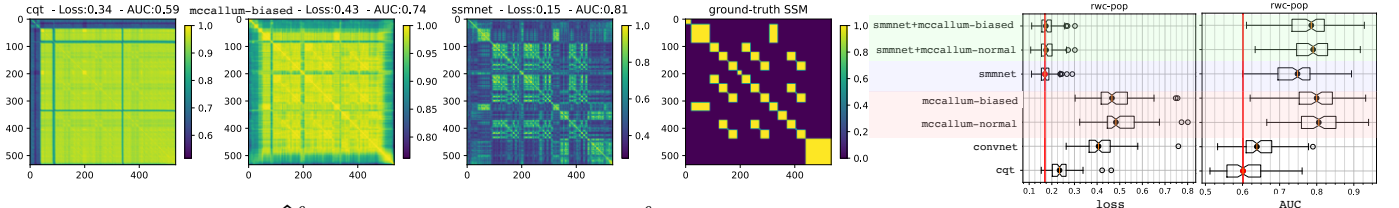
<sup>4</sup> using constrained agglomerative clustering and median aggregation as implemented in `librosa.segment.subsegment`.

<sup>5</sup> f and t denotes the frequency and time dimensions





**Figure 1.** SSM-net architecture. From left to right: input sequence  $\{\mathbf{X}_i\}$  of beat-synchronous CQT-patches, encoder  $f^\theta$  applied to each  $\mathbf{X}_i$ , estimated SSM  $\hat{\mathbf{S}}_{ij}^\theta$  computed with embeddings  $\{e_i^\theta\} = f^\theta(\{\mathbf{X}_i\})$ , Loss  $\mathcal{L}^\theta$  computation.



**Figure 2.** [Left] SSMs  $\hat{\mathbf{S}}_{ij}^\theta$  computed using embeddings  $e^\theta$  obtained using (from left to right): cqt, mccallum-biased, ssmnet and ground-truth SSM  $\mathbf{S}_{ij}$ , on track 2 from RWC-Pop dataset. Loss  $\mathcal{L}$  and AUC are indicated on top of each. [Right] Box-plots of Loss  $\mathcal{L}$  and AUC obtained for all tracks of RWC-Pop dataset.

(a set of  $T^2$  binary classifications) and minimize the sum of Binary-Cross-Entropy (BCE) losses. We compensate the class unbalancing by using a weighting factor  $\lambda$  computed as the percentage of 1 values in  $\mathbf{S}_{ij}$ .

$$\mathcal{L}^\theta = - \sum_{i,j=1}^T (1 - \lambda) [\mathbf{S}_{ij} \log(\hat{\mathbf{S}}_{ij}^\theta)] + \lambda [(1 - \mathbf{S}_{ij}) \log(1 - \hat{\mathbf{S}}_{ij}^\theta)] \quad (3)$$

Since the computation of the SSM  $\hat{\mathbf{S}}_{ij}^\theta$  is differentiable w.r.t. to the embeddings  $\{e_i^\theta\}$ , we can compute  $\frac{\partial \mathcal{L}^\theta}{\partial \theta}$

$$\frac{\partial \mathcal{L}^\theta}{\partial \theta} = \sum_{i,j=1}^T \frac{\partial \mathcal{L}^\theta}{\partial \hat{\mathbf{S}}_{ij}^\theta} \left( \frac{\partial \hat{\mathbf{S}}_{ij}^\theta}{\partial e_i^\theta} \frac{\partial e_i^\theta}{\partial \theta} + \frac{\partial \hat{\mathbf{S}}_{ij}^\theta}{\partial e_j^\theta} \frac{\partial e_j^\theta}{\partial \theta} \right) \quad (4)$$

**Training.** We minimize the loss using MAD-GRAD [14] with a learning rate of  $5 \times 10^{-4}$ , a weight decay of  $10^{-2}$  and early-stopping. The mini-batch-size  $m$  (here defined as the number of full-tracks) is set to 6.

**Generating a ground-truth SSM  $\mathbf{S}_{ij}$ .** To generate  $\mathbf{S}_{ij}$ , we rely on the homogeneity assumption, i.e. we suppose that all  $t_i$  that fall within an annotated segment are identical since they share the same label. If we denote by  $\text{seg}(t_i)$  the segment  $t_i$  belongs to and by  $\text{label}(\text{seg}(t_i))$  its label, we assign the value  $\mathbf{S}_{ij} = 1$  if  $\text{label}(\text{seg}(t_i)) = \text{label}(\text{seg}(t_j))$ .

### 3. EVALUATION

To evaluate the quality of the features independently of the choice of a specific detection algorithm for MSA, we directly compare the ground-truth  $\mathbf{S}_{ij}$  and the  $\hat{\mathbf{S}}_{ij}^\theta$  obtained using various choices for  $e^\theta$ . For each choice, we measure

the obtained Loss  $\mathcal{L}$  (lower is better) and AUC (higher is better). We consider the following features  $e^\theta$ :

- cqt: the flattened CQT patches  $\{\mathbf{X}_i\}$
- convnet: the output of the un-trained (random weight) encoder  $f^\theta$  applied to  $\{\mathbf{X}_i\}$
- ssmnet: the output of  $f^\theta$  trained with SSM-Net
- mccallum-normal/biased: the output of the same encoder  $f^\theta$  but trained using the two unsupervised metric learning approaches described in [6]
- ssmnet-mccallum-normal/biased: same as for ssmnet but  $f^\theta$  is pre-trained using mccallum-normal/biased

To train our SSM-Net, we used a sub-set of 695 tracks from the labeled dataset Harmonix [15]. To train the unsupervised metric learning approach described in [6], we used a large unlabeled dataset from YouTube of 26.000 tracks from various genres. The evaluation is performed on RWC-Pop [16] labeled with AIST annotations [17]).

In Figure 2 [Left], we give an example of the SSM  $\hat{\mathbf{S}}_{ij}^\theta$  obtained using the embeddings  $e^\theta$  learned by the most representative approaches. On this example, ssmnet gives the  $\hat{\mathbf{S}}_{ij}^\theta$  with the highest contrast and the closest to the ground-truth. It gets a small  $\mathcal{L}=0.15$  and a high  $\text{AUC}=0.81$ .

In Figure 2 [Right], we represent the box-plots of  $\mathcal{L}$  and AUC considering all tracks of RWC-Pop. As one can see, the SSM-net approach leads to the lowest  $\mathcal{L}$ . However McCallum leads to a higher AUC than SSM-Net. We therefore combine the SSM-Net training with a McCallum pre-training. This then leads to both a low  $\mathcal{L}$  and a high AUC. This is the approach we will develop in the future.

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