

CITY UNIVERSITY OF HONG KONG

RESEARCH PROJECT REPORT

Sequence Model Evolution: A Time Series Analysis Viewpoint

Author:

Zeyin LIN
Yuzhan LIU
Ziyi PU

Supervisor:

Dr. Xinyue LI

Master of Science in Data Science

School of Data Science

February 25, 2021

CITY UNIVERSITY OF HONG KONG

Abstract

School of Data Science

Master of Science in Data Science

**Sequence Model Evolution:
A Time Series Analysis Viewpoint**

by Zeyin LIN
Yuzhan LIU
Ziyi PU

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Contents

Chapter 1

Introduction to Time Series Analysis

1.1 What Is A Time Series

A time series is a sequential set of data points, measured typically over successive times

1.1.1 Categories

- univariate vs. multivariate. A time series containing records of a single variable is termed as univariate, but if records of more than one variable are considered then it is termed as multivariate.
- linear vs. non-linear. A time series model is said to be linear or non-linear depending on whether the current value of the series is a linear or non-linear function of past observations.
- discrete vs. continuous. In a continuous time series observations are measured at every instance of time, whereas a discrete time series contains observations measured at discrete points in time.

1.1.2 Components of a Time Series

- Trend
- Seasonal variation
- Cyclical variation
- Irregular variation

1.2 How to identify time series anomaly period

Time series anomaly detection can be transformed into a task where the goal is to model the time series. Given this model, it finds periods where the predicted values are significantly different from the actual normal ones. Traditionally, researchers use ARMA, ARIMA, GARCH, and other statistics-based methods to do modeling tasks.

1.3 Statistical Methods and Comparassion

TODO: Stationarity and Whithe noise

1.3.1 AR and MA

TODO: Details

1.3.2 ARMA and ARIMA

TODO: Details

1.3.3 GARCH

TODO: Details

1.4 Architecture of This Report

- Chapter 1: Introduction to Time Series Analysis Problem and Statistical Methods
- Chapter 2: Deep Learning theory and Related Derivative
- Chapter 3: Experiment Framework and Settings
- Chapter 4: Details of experiment 1 (Reporducing Bai's demo)
- Chapter 5: Details of experiment 2 (Reimplement methods with stock)
- Chapter 6: (optional) Details of experiment 3 (Revolutional methods and its perfomance)
- Chapter 7: Discussion of the experimental results
- Chapter 8: Conclusion and future directions

Chapter 2

Deep Learning theory and Related Derivated

TODO: Unif in symbols

2.1 Recurrent Neural networks

Artificial neural networks usually only fetch and process one input individually, and the previous input has nothing to do with the next input. However, some tasks need to handle sequence information better, which means the previous input is related to the subsequent input. In this kind of problem, former researchers Graves and Alex(2009) designed the recurrent neural network (RNN), which is a class of artificial neural networks where connections between nodes form a directed graph along a temporal sequence. This allows it to exhibit temporal dynamic behavior. Derived from feedforward neural networks, RNNs can use their internal state (memory) to process variable-length sequences of inputs.

Sepp Hochreiter and Jürgen Schmidhuber (1997) post the practical method under the concept of RNN, that is, Long short-term memory (LSTM) architecture, with both feedforward neural networks and feedback connections. This makes them applicable to tasks such as unsegmented, connected handwriting recognition, or speech recognition.

2.2 Convolutional Neural Networks

Convolutional Neural Networks(CNNs) were originally used on two-dimensional and three-dimensional images, but they are also suitable for one-dimensional data such as univariate time series. Shaojie Bai, J. Zico Kolter, and Vladlen Koltun(2018) designed the architecture temporal convolutional network(TCN) and ran it into image, sound, and text level tasks. This work inspired that convolutional networks could reach the same even better results as other sequence models. Alberto(2019) experimented with TCN and other sequence models in smart grids situations, also found that convolutional networks are significantly useful in time series tasks. However, Seq2Seq methods still hold the best performance place.

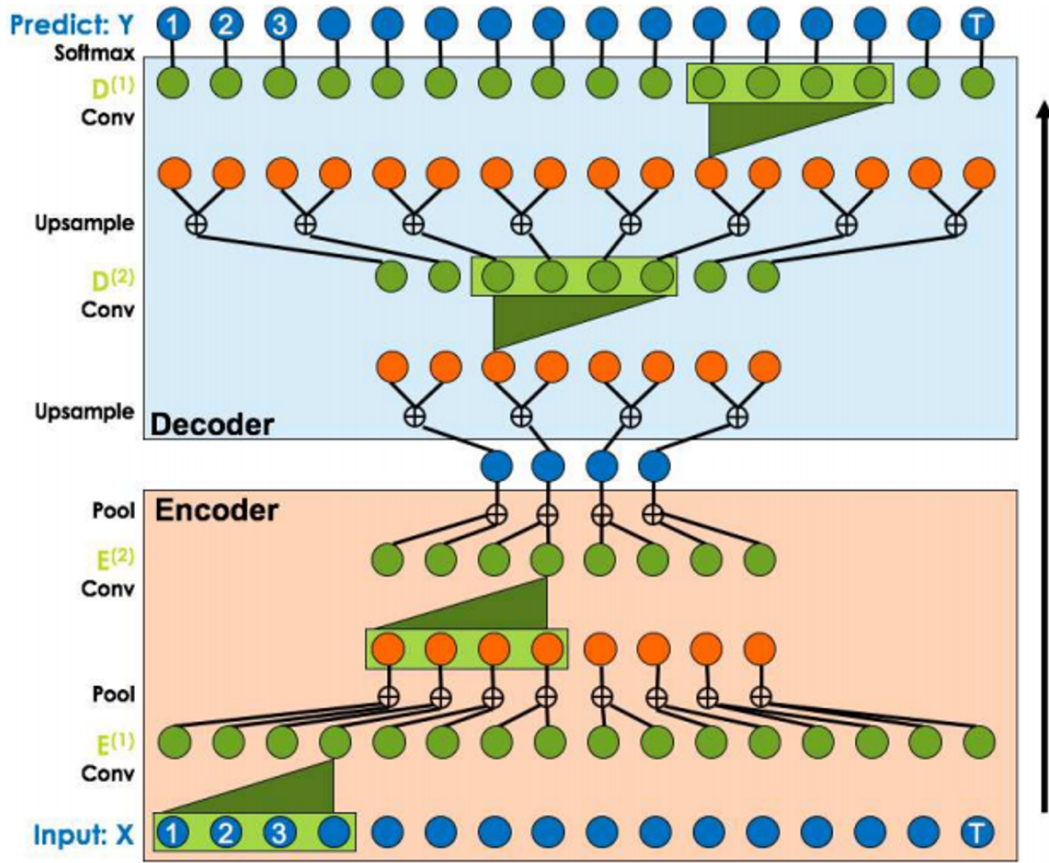
2.2.1 The origin of TCN

The Temporal Convolutional Networks (TCNs) was first proposed by the work of Lea et al. (2016) for video-based action segmentation. The two steps of this conventional process include: firstly, computing of low-level features using (usually) CNN

that encode spatial-temporal information and secondly, input these low-level features into a classifier that captures high-level temporal information using (usually) RNN. The main disadvantage of such an approach is that it requires two separate models. TCN provides a unified approach to capture all two levels of information hierarchically.

Encoder-Decoder TCN

The encoder-decoder framework is presented in below, where further information regarding the architecture can be found in the first two references (at the end of the post). The most critical issues are provided as follows: TCN can take a series of any length and output it as the same length. A causal convolutional is used where a 1D fully convolutional network architecture is used. A key characteristic is that the output at time t is only convolved with the elements that occurred before t . The encoder



consists of L layers denotes by $E^l \in R^{F_l \times T_l}$ where F_l is the number of convolutional filters in a the l -th layer and T_l is the number of corresponding time steps. Each layer consists of temporal convolutions, a non-linear activation function, and max pooling across time. We define the collection of filters in each layer as $W = W_{i=1}^{(i)F_l}$ for $W^{(i)} \in R^{d \times F_{l-1}}$ with a corresponding bias vector $b \in R^{F_l}$. Given the signal from the previous layer, $E^{(l-1)}$, we compute $E^{(l)}$ activations with

$$E^{(l)} = \text{maxpooling}(f(W \times E^{(l-1)} + b))$$

, where $f(\cdot)$ is the activation function and \star is the (same) convolution operator. After each activation function we max pool with width 2 across time so $T_l = \frac{1}{2}T_{l-1}$. Pooling enables us to efficiently compute activations over long temporal windows.

The decoder is similar to the encoder, except that upsampling is used instead of pooling and the order of the operations is now upsample, convolve, and apply the activation function. Upsampling is performed by simply repeating each entry twice. The convolutional filters in the decoder distribute the activations from the condensed layers in the middle to the action predictions at the top. Experimentally, these convolutions provide a large improvement in performance and appear to capture pairwise transitions between actions. Each decoder layer is denoted by $D^{(l)} \in R^{F_l \times T_l}$ for $l = L, \dots, 1$. Note that these are indexed in reverse order compared to the encoder, so the filter count in the first encoder layer is the same as in the last decoder layer. The probability that frame corresponds each of the C action classes is given by vector $\hat{Y}_t \in [0, 1]^C$ using weight matrix $U \in R^{C \times F_1}$ and bias $c \in R^C$, such that

$$\hat{Y}_t = \text{softmax}(UD_t^{(1)} + C)$$

We explored other mechanisms, such as skip connections between layers, different patterns of convolutions, and other normalization schemes, however, the proposed model outperformed these alternatives and is arguably simpler.

Dilated TCN

As shown in ??, we define a series of blocks, each of which contains a sequence of L convolutional layers. The activations in the l -th layer and j -th block are given by $S^{(j,l)} \in R^{(F_w \times T)}$. The input into each block $S^{(j,1)}$ is the output from the previous block $S^{(j-1,L)}$, except for the first block which is defined as the input data. Each layer has the same number of filters F_w , which enables us to combine activations from different layers using skip connections later. Each layer consists a set of dilated convolutions with rate parameter s , a non-linear activation $f(\cdot)$, and a residual connection that combines the layers input and the convolution signal. Convolutions are only applied over two-time steps, t and $t - s$, so we write out the full equations below.

The filters are parameterized by $W = \{W^{(1)}, W^{(2)}\}$ with $W^{(i)} \in R^{F_w \times F_w}$ and bias vector $b \in R^{F_w}$. Let $\hat{S}_t^{(j,l)}$ be the result of the dilated convolution at time t and $S_t^{j,l}$ be the result after adding the residual connection such that

$$\hat{S}_t^{(j,l)} = f(W^{(1)}S_{t-s}^{(j,l-1)} + W^{(2)}S_t^{(j,l-1)} + b)$$

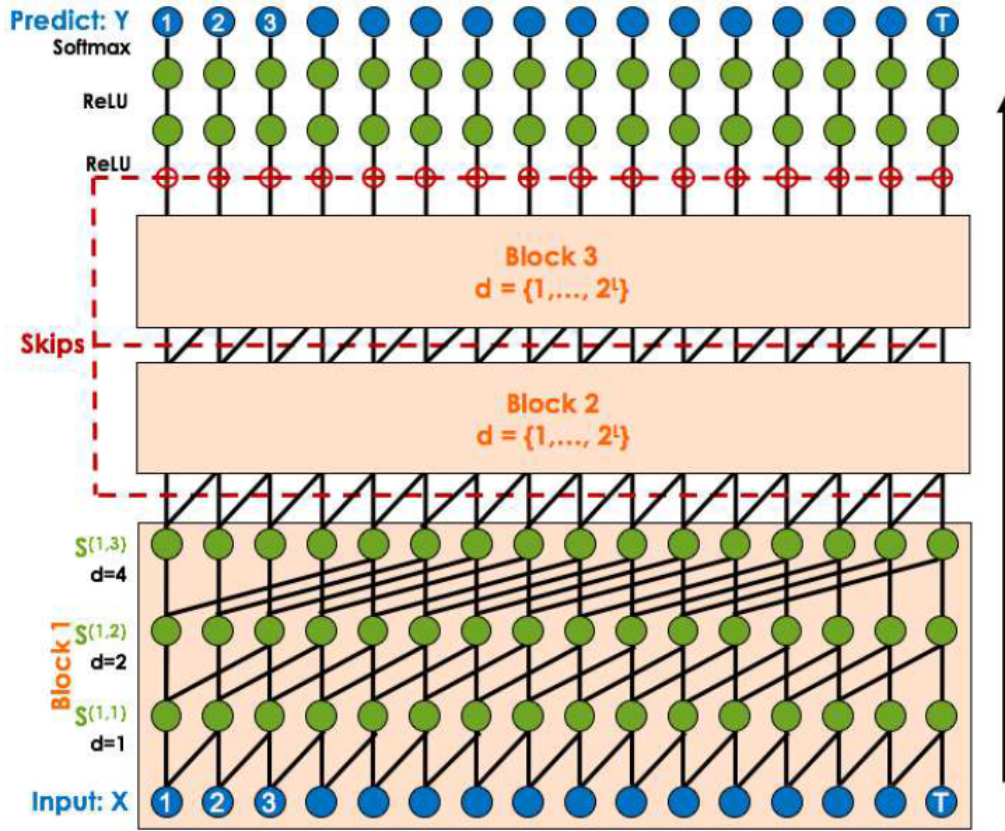
Let $V \in R^{F_w \times F_w}$ and $e \in R^{F_w}$ be a set of weights and biases for the residual. Note that parameters $\{W, b, V, e\}$ are separate for each layer. The dilation rate increases for consecutive layers within a block such that $s_l = 2$. This enables us to increase the receptive field by a substantial amount without drastically increasing the number of parameters. The output of each block is summed using a set of skip connections with $Z^{(0)} \in R^{(F_w \times T)}$ such that

$$Z^{(0)} = \text{ReLU}(\sum_{j=1}^B S_t^{(j,l)})$$

There is a set of latent states $Z_t^{(1)} = \text{ReLU}(V_r Z_t^{(0)} + e_r)$ for weight matrix $V_r \in R^{F_w \times F_w}$ and bias e_r . The predictions for each time t are given by

$$\hat{Y}_t = \text{softmax}(UZ_t^{(1)} + C)$$

for weight matrix $U \in R^{C \times F_w}$ and bias $c \in R^C$.



2.2.2 Further development and description of TCN

S. Bai et al. (2018) suggest that convolutional networks should be taken into consideration as one of the primary candidates when modeling sequential data. They were able to show that convolutional networks can achieve better performance than RNNs in many tasks while avoiding common drawbacks of recurrent models, such as the exploding/vanishing gradient problem or lacking memory retention. Furthermore, using a convolutional network instead of a recurrent one can lead to performance improvements as it allows for parallel computation of outputs. They suggest a few additions to the basic TCN architecture for improved performance which will be discussed in this section, namely residual connections, regularization and activation functions.

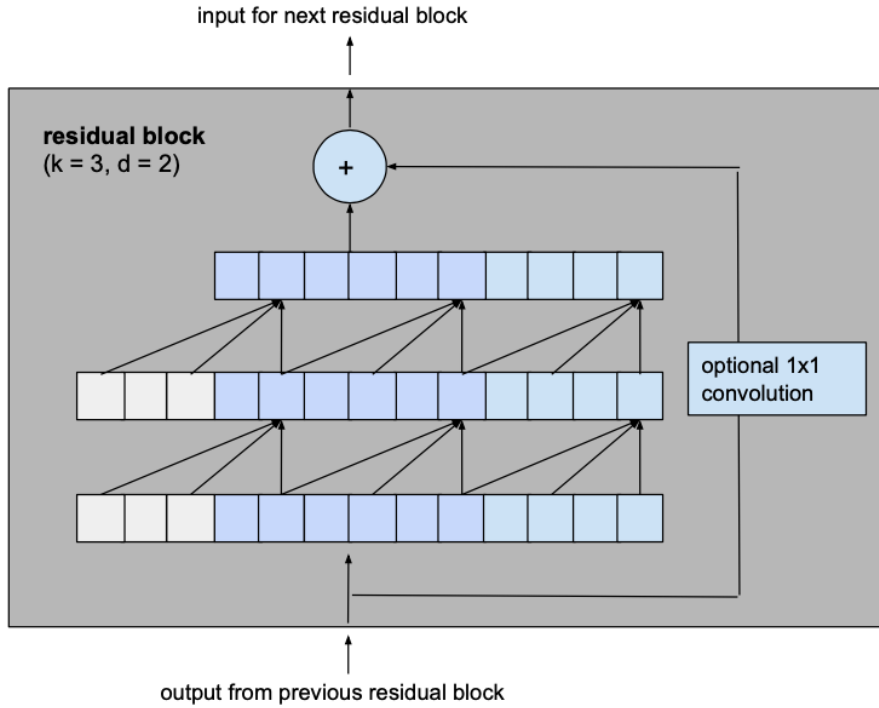
Residual Blocks

The biggest modification we make to the previously introduced basic model is to change the fundamental building block of the model from a simple 1D causal convolutional layer to a residual block which consists of 2 layers with the same dilation factor and a residual connection.

A residual block contains a branch leading out to a series of transformations F , whose outputs are added to the input x of the block:

$$o = \text{Activation}(x + F(x))$$

Lets consider a layer with a dilation factor d of 2 and kernel size k of 3 from the basic model to see how this translates into a residual block of the improved model.



The output of the two convolutional layers will be added to the input of the residual block to produce the input for the next block. For all inner blocks of the network, i.e. all but the first and the last one, the input and output channel width is the same, namely `num_filters`. Since the first convolutional layer of the first residual block and the second convolutional layer of the last residual block may have different input and output channel widths, the width of the residual tensor might have to be adjusted, which is done using a 1×1 convolution.

This change affects the calculus for the minimum number of required layers for full coverage. Now we have to think about how many residual blocks are necessary to achieve a full receptive field coverage. Adding a residual block to a TCN adds twice as much receptive field width than when adding a basic causal layer, since it includes 2 such layers. So the total size of the receptive field r of a TCN with dilation base b , kernel size k with $k \geq b$ and number of residual blocks n can be computed as

$$r = 1 + \sum_{i=0}^{n-1} 2(k-1)b^i = 1 + 2(k-1) \times \frac{b^n - 1}{b - 1}$$

, which leads to a minimum number of residual blocks for full history coverage of input_length l of

$$n = \left\lceil \log_b \left(\frac{(l-1)(b-1)}{2(k-1)} + 1 \right) \right\rceil$$

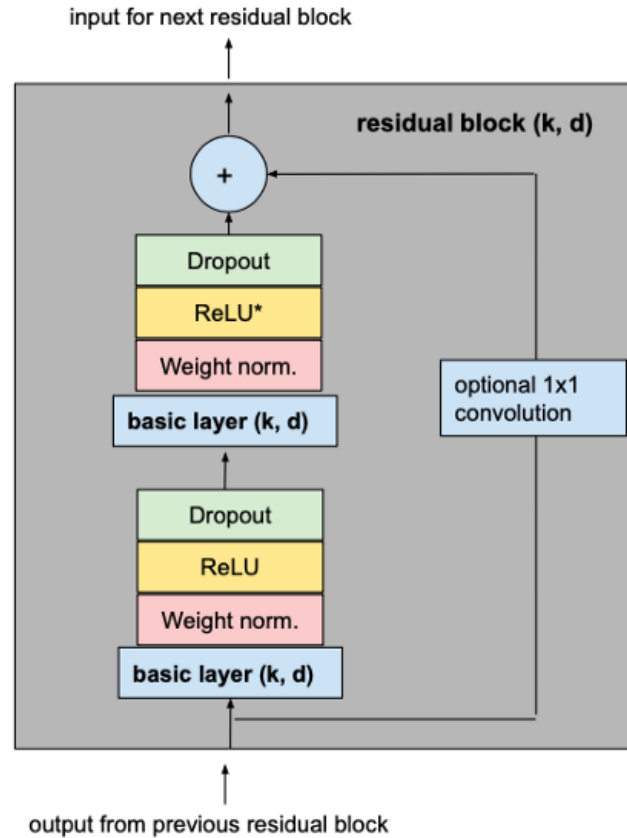
Activation, Normalization, Regularization

To make our TCN more than just an overly complex linear regression model, activation functions need to be added on top of the convolutional layers to introduce

non-linearities. *ReLU* activations are added to the residual blocks after both convolutional layers.

To normalize the input of hidden layers (which counteracts the exploding gradient problem among other things), weight normalization is applied to every convolutional layer.

In order to prevent overfitting, regularization is introduced via dropout after every convolutional layer in every residual block. The following figure shows the final residual block. The asterisk in the second *ReLU* unit indicates that it is present



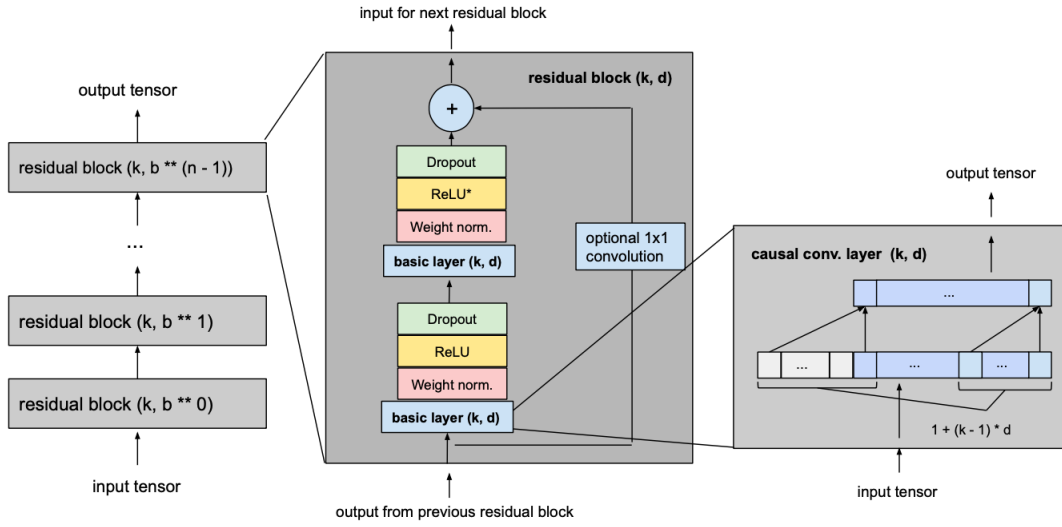
in every layer but the last one, since we want our final output to be able to take on negative values as well (this differs from the architecture outlined in the paper).

The following picture shows our final TCN model with l equal to input_length, k equal to kernel_size, b equal to dilation_base, $k \geq b$ and with a minimum number of residual blocks for full history coverage, where n can be computed from the other values as explained above.

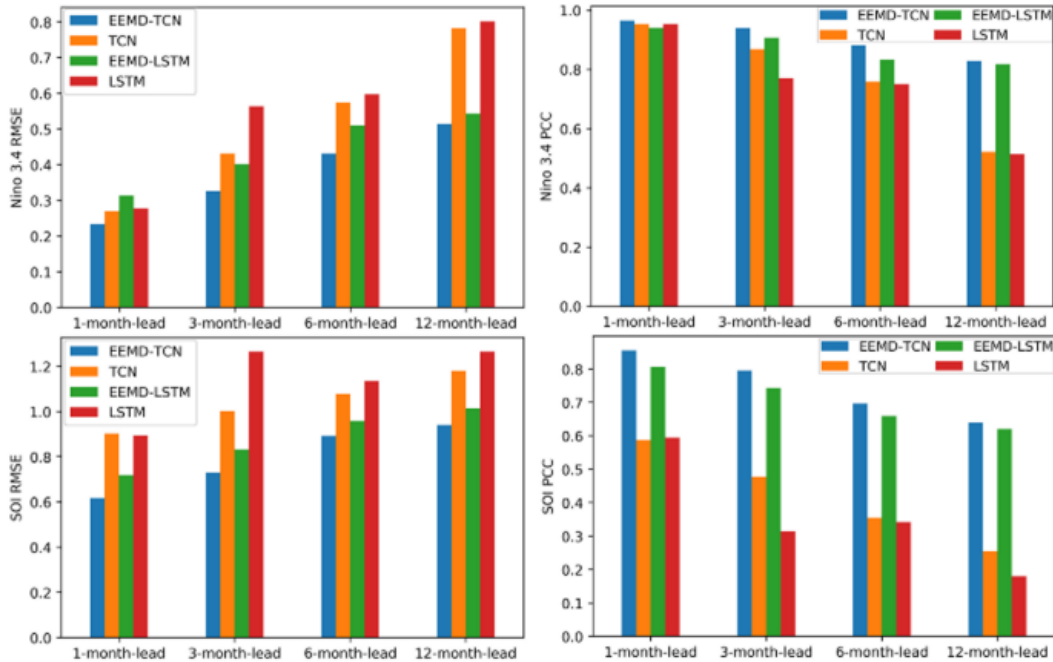
2.2.3 Applications of TCN

Weather prediction

The buzz around TCN arrives even to Nature journal, with the recent publication of the work by Yan et al. (2020) on TCN for weather prediction tasks. In their work, a comparative experiment was conducted with TCN and LSTM. One of their results was that, among other approaches, the TCN performs well in prediction tasks with time-series data. In the paper, the author introduces a mode called ensemble empirical mode decomposition (EEMD). EEMD not only can decompose high-frequency



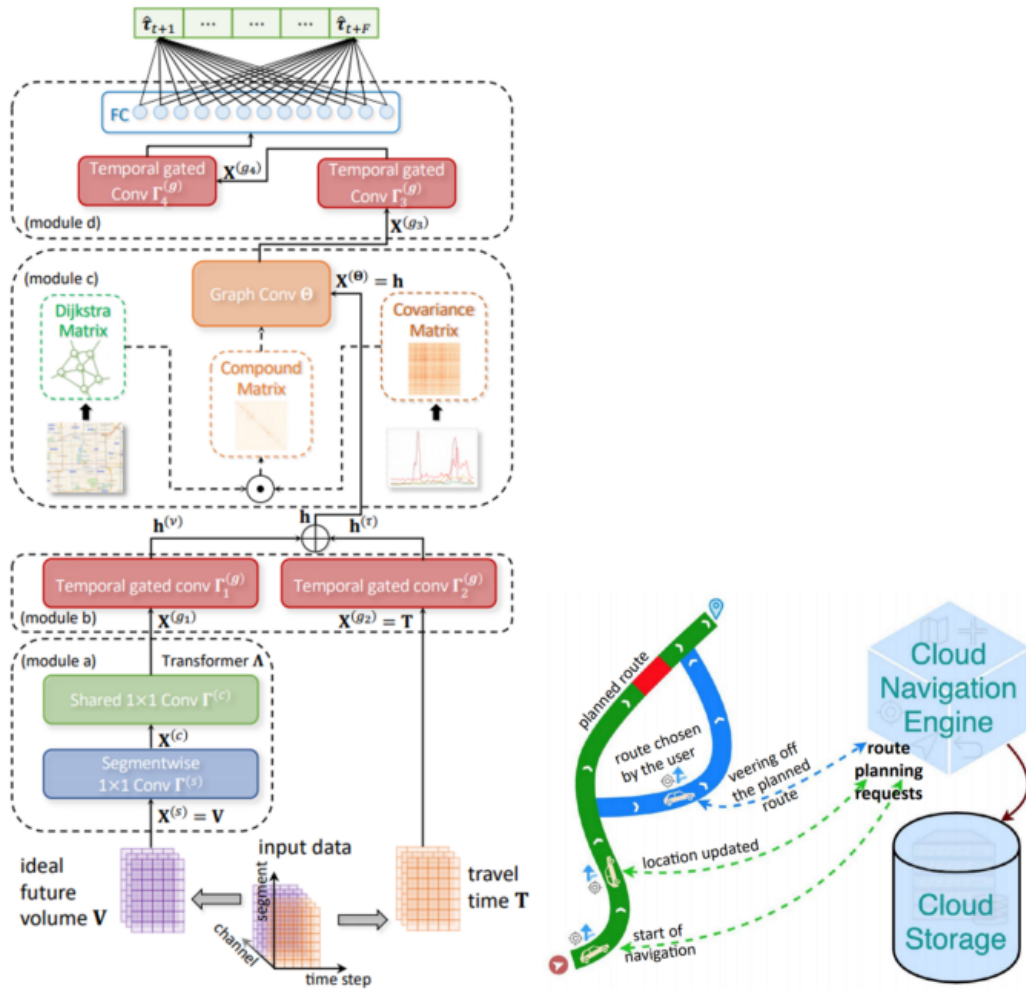
time series into some adaptive orthogonal components, called intrinsic mode functions (IMFs), but also has the advantages of noise-assistance and overcoming the drawbacks of mode mixing in conventional empirical mode decomposition (EMD). EEMD can be used to decompose the high-frequency time-series Niño 3.4 index and SOI data into multiple adaptive orthogonal components to improve the prediction accuracy of the model. Therefore, this paper proposes the EEMD-TCN hybrid approach, which is used to decompose the highly variable ENSO indexes (Niño 3.4 index and SOI) into relatively flat subcomponents, and then uses the TCN model to predict each subcomponent in advance, finally combining the sub-prediction results to obtain the final ENSO prediction results.



Traffic prediction

Ride-sharing and online navigation services can improve traffic prediction and change the way of life on the road. Fewer traffic jams, less pollution, safe and fast driving

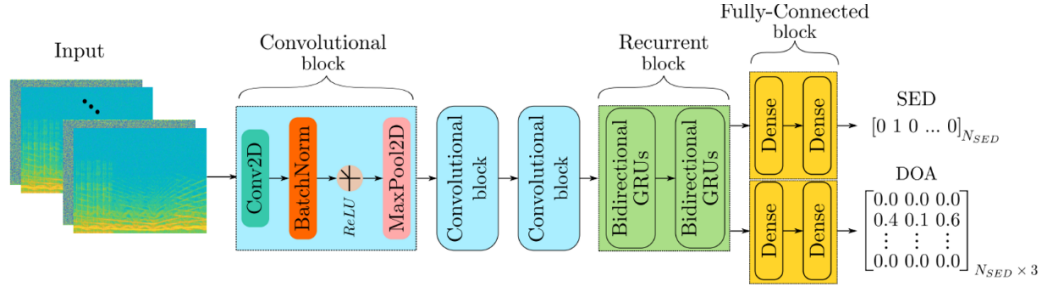
are just a few examples of essential issues that can be achieved by better traffic predictions. As this is a real-time data-driven problem, it is necessary to utilize the accumulated data of upcoming traffic. For this reason, Dai et al. (2020) recently presented a Hybrid Spatio-Temporal Graph Convolutional Network (H-STGCN). The general idea is to take the advantages of the piecewise-linear-flow-density relationship and convert the upcoming traffic volume in its equivalent in travel time. One of the most interesting approaches they used in this work is the graph convolution to capture the spatial dependency. The compound adjacency matrix captures the innate characteristics of traffic approximation. In the following architecture, four modules are presented to describe the entire prediction process. In this paper, they describe the overall architecture of H-STGCN, as illustrated in figure below. The model input consists of two feature tensors, the ideal-future-volume tensor V and travel-time tensor T . Specifically, both V and T have three dimensions: the spatial dimension, temporal dimension, and channel dimension, which corresponds respectively to the road segments, previous time slots utilized, and features.



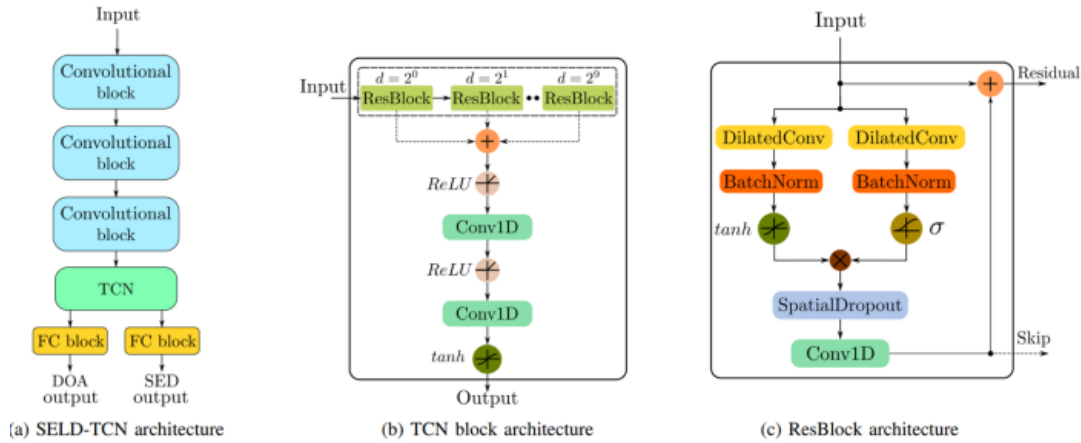
Sound event localization and detection

The field of sound event localization and detection (SELD) continues to grow. Understanding the environment plays a critical role in autonomous navigation. Guirguis et al. (2020) recently proposed a novel architecture for sound events SELD-TCN.

They claim that their framework outperforms the state-of-the-art in the field, with faster training time. In their SELDnet (architecture below), a multichannel audio recording, sampled at 44.1 kHz, extracts, by applying a short-time Fourier transformation, the phase and magnitude of the spectrum, and stacks it as separate input features. Then, convolutional blocks and recurrent blocks (bi-directional GRUs) are connected, followed by a fully-connected block. The output of the SELDnet is the SOUND Event Detection (SED) and Direction Of Arrival (DOA). In order to outper-



form it, they present the SELD-TCN: The aforementioned SELDnet architecture is

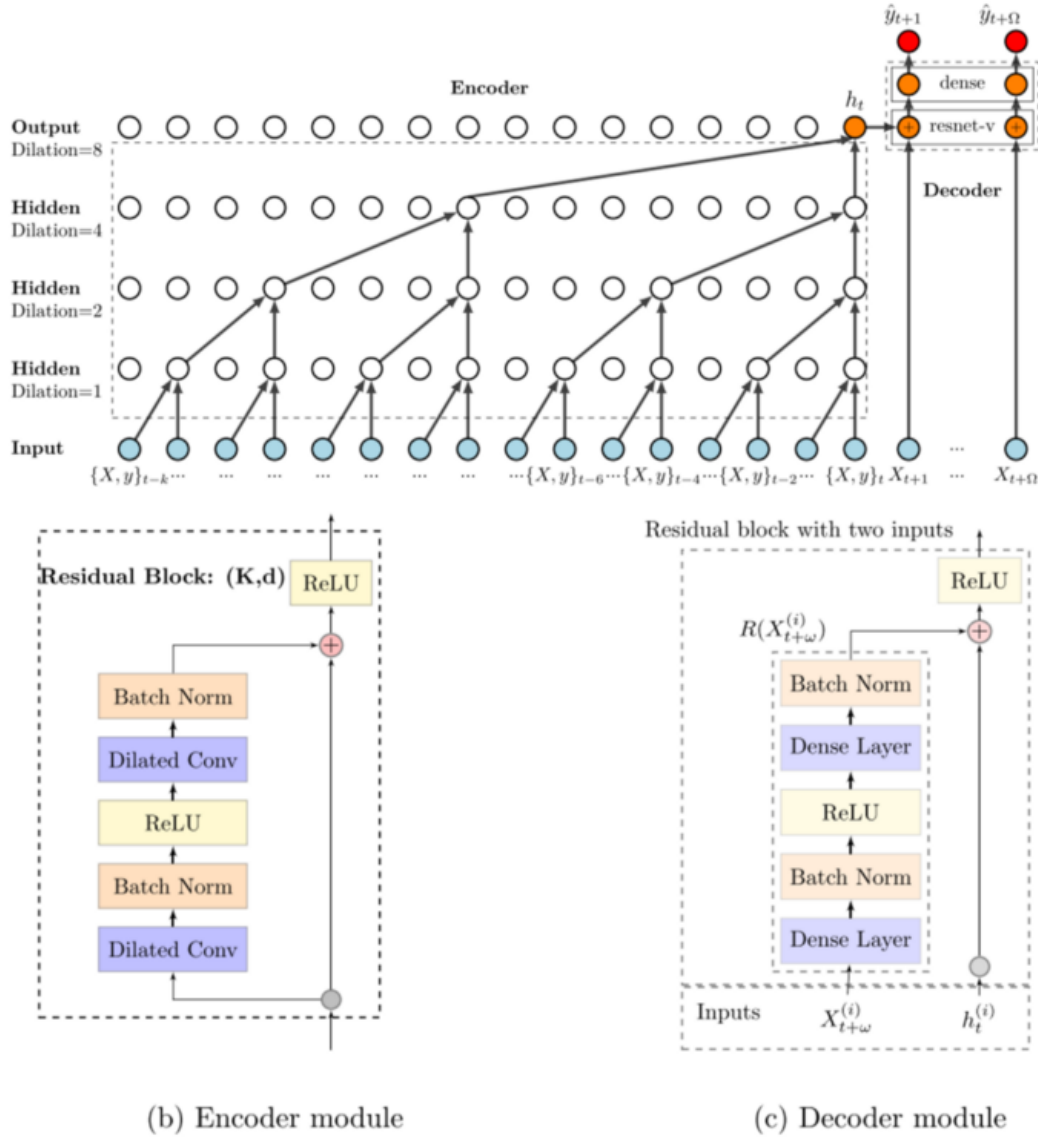


used while replacing the recurrent block by a TCN, where they adopt the WaveNet architecture. Fig. b shows an overview of the proposed TCN block architecture. Then, to mimic the bidirectional RNNs use of future knowledge, they modify all convolutions within the TCN block to be non-causal. In this implementation, they use 10 residual blocks (ResBlocks) with dilation rates $d = [2^0, 2^1, \dots, 2^9]$. As shown in above figure, the ResBlock consists of 1D dilated convolutions with 256 filters of size 3 and a dilation rate d . As the dilated convolutions enable the net to process a variety of inputs, a more in-depth network may be required (which will be affected by unstable gradients during backpropagation). They overcome this challenge by adapting the WaveNet (Dario et al., 2017) architecture. They showed that the recurrent layers are not required for SELD tasks, and successfully detected the start and the end times of active sound events.

Probabilistic forecasting

A novel framework designed by Chen et al. (2020) can be applied to estimate probability density. Time series prediction improves many business decision-making scenarios (for example, resources management). Probabilistic forecasting can extract information from historical data and minimize the uncertainty of future events.

When the prediction task is to predict millions of related data series (as in the retail business), it requires prohibitive labor and computing resources for parameter estimation. In order to solve these difficulties, they proposed a CNN-based density estimation and prediction framework. Their framework can learn the latent correlation among series. The novelty in their work is the deep TCN they proposed, as presented in their architecture: (a) The architecture of Deep-TCN. Encoder part: stacked



dilated causal convolutional nets are constructed to capture the long-term temporal dependencies. Decoder part: the decoder includes a variant of residual block (referred as resnet-v, shown as) and an output dense layer. The module resnet-v is designed to integrate output of stochastic process of historical observations and future covariates. Then the output dense layer is adopted to map the output of resnet-v into final forecasts. (b) Encoder module. Residual blocks are taken as the ingredient. Each residual block consists of two layers of dilated causal convolutions, the first of which is followed by a batch normalization and ReLU and the second of which is followed by another batch normalization. The output is taken as the input of the residual block, followed by another ReLU. (c) Decoder module. The decoder includes two

In the KDTCN architecture, the original model inputs are price values, news corpus, and knowledge graph. The price values are normalized and mapped into the price vector, denoted by

where each vector represents a real-time price vector on a stock trading day, and is the time span. Pieces of news are represented as event sets, and event tuple is defined as, where is the action or predicate, is the actor or subject and is the object on which the action is performed. Then, each item in event tuples is linked to KG. Note that event items in this paper refer to the, and in the event tuple, and they also correspond to entities and relations in KG. They obtain event embeddings by training both event tuples and KG triples. They propose and to define the entity and relation in an event tuple linked to KG, as well as to define the immediate neighbors of linked entities in KG, denoted by

Then they parameterize event representations in different channels, denoted by in the channel of KG linking, in the channel of KG context, and in the channel of words.

where, and; , and; and are the word vectors of, and respectively; represents the embedding of. Then we concatenate, and in multiple channels to get the final event embedding, denoted by

Finally, event embeddings, combined with price vectors are input into a TCN-based model for stock trend prediction and explanation particularly with abrupt changes.

2.3 Other Derivatives(eg. Transformer)

Several papers have studied using basic and modified attention mechanisms for time series data. LSTNet(Guokun Lai(2018)) is one of the papers that proposes using an LSTM + attention mechanism for multivariate forecasting time series. Temporal Pattern Attention for Multivariate Time Series Forecasting by Shun-Yao Shih et al. focused on applying attention specifically for multivariate data. This mechanism aimed to resolve issues including noisy variables in the multivariate time series and introduce a better method than a simple average. Neo Wu et al.(2020) employed Transformer-based machine learning models to forecast time series data. This approach works by leveraging self-attention mechanisms to learn complex patterns and dynamics from time-series data.

Chapter 3

Experiment Framework and Settings

3.1 Programming Environment

For all the experiments in this project, we will use Python3 with Pandas, Numpy, and TensorFlow packages. And we use CityU Burgundy HPC as part of our hardware supports.

Chapter 4

Details of experiment 1

4.1 Target of experiment 1

4.2 Data Processing

4.3 Models in detail

4.4 Numeric results

Appendix A

Online Resources

A.1 Experiment Code

This project owns a open source code repo at [Github Repository of Time Series Anomaly Detection](#).