

Multi-speaker articulatory-to-acoustic speech synthesis with deep neural networks

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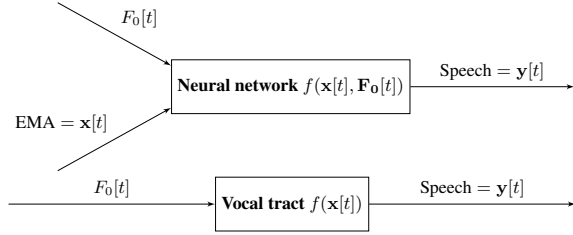


Figure 1: Black box diagram showing the parallelities of a neural network based model with a source-filter model

Abstract

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Index Terms: computational paralinguistics, articulatory-to-acoustic speech synthesis, deep learning, pathological speech

1. Introduction

Understanding how articulation affects speech is a central question in speech research. The source-filter model was one of the first models to tackle this problem by noting that speech production could be described by the geometry of the vocal tract and the glottal wave. Mathematically, the source-filter model synthesises speech by exciting an autoregressive (AR) model with a signal, where the AR coefficients capture the geometry of the vocal tract, which is also represented by an area function [1].

Recently, deep learning methods became popular to understand articulation. These methods use a measurement tool, called electromagnetic articulography to obtain articulation data [2] [3] [4] along with recurrent neural networks, which are neural networks that are able to deal with the sequential nature of data. Data-driven methods became of interest also in real-time speech synthesis. The efficacy of real-time speech synthesis has been investigated using a tool called permanent magnetic articulography by Gonzalez et al [5], which gave understandable speech.

The conclusion of these endeavours were that while it is possible to predict some of the pitch from articulation, the quality suffers. It is, however, possible to obtain satisfactory values for the spectral quality.

In the author's broader research, the aim is to demonstrate how pathologies in articulation are translated to speech. In some types of pathological speech the laryngeal function remains intact, meaning the F_0 remains unchanged. This means, by knowing the original pitch and the pathological deviations in articulation, it should be possible to synthesise pathological speech.

Furthermore, based on the principles of the source-filter model, neural network based speech synthesis should then have the F_0 on the input side of the model, rather than as a predicted value. This separates source information (excitation and articulation) from the effect (speech) and the neural network can then be looked as a function approximator for a dynamic area function.

The main contributions of this paper are,

- a set of benchmarks for multi-speaker articulatory to acoustic synthesis
- estimation on how much data would be needed to construct a better model
- an example of how to construct pathological speech using this framework

Our code is also available as a Github repository on the link <https://github.com/karkiorowle/vocoder-clean>.

2. Method

2.1. Electromagnetic articulography

Electromagnetic articulography (EMA) is a measurement technology which uses sensor coils which are placed on the different articulators in the vocal tract. Using this technology it is possible to record the displacement of the articulators which can then be used to predict speech which is simultaneously recorded.

The electrodes are placed on the MNGU0 [6] and MOCHA-TIMIT dataset on a total of seven positions. The two datasets have not recorded entire the same channels, so Table ?? include the alignment that has been used.

TODO: Decide whether you want to leave out the lower incisor or jaw

2.2. Dataset

The MNGU0 and the MOCHA-TIMIT dataset were used to obtain a total of 2274 samples, which were partitioned to training and validation set when no hyperparameter optimisation was done. An additional test set was used in case of hyperparameter optimisation. The dataset contains data from three speakers,

Table 1: *Articulatory information recorded in datasets*

MNGU0	MOCHA-TIMIT
Tongue dorsum (T3)	Tongue dorsum (T3)
Tongue blades (T2)	Tongue blades (T2)
Tongue tip (T1)	Tongue tip (T1)
Lower incisor (T3)	Jaw
Upper incisor	Nose
Upper lip	Upper lip
Lower lip	Lower lip

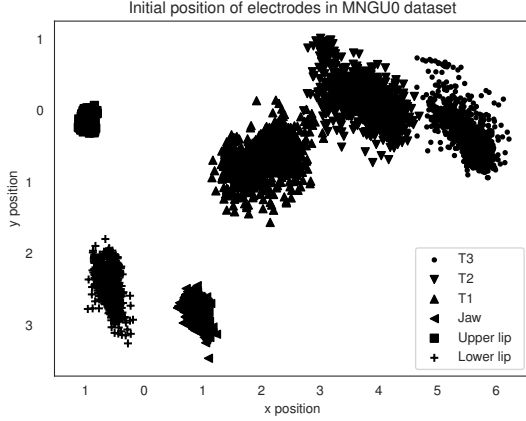


Figure 2: *The visualisation of electrode locations for all samples in the MNGU0 dataset at time point $t = 0$*

two British male and one British female. The recordings from the microphones were 16kHz.

2.3. Sampling

It is important that the input and output sample rates of the different datasets are matched, because otherwise, the input-output pairs contain different amounts of information.

The sampling frequency of the original EMA signals were 500 Hz, however the MNGU0 was provided to us downsampled to 200 Hz. To match this frequency, the sampling frequency of the MOCHA-TIMIT were also downsampled to 200 Hz.

For the MNGU0 dataset, NaN values occurred when the measurement precision was lost. These values were simply interpolated linearly.

To ease training, the input signals were either truncated or padded so there were a total of $T = 1000$ samples for each training example. For input signals which are shorter, it is assumed that the last part is silence, so it is padded with the last element.

2.4. Vocoder analysis

Vocoder features were extracted with the PyWORLD vocoder [7] and compressed with the PySPTK toolkit available at <http://github.com/r9y9/pysptk>. The period between consecutive frames were 5 milliseconds. The resulting 40 MFCC and 1 power parameters were used to generate static and delta parameters, resulting in 82 parameters for the training. As the first step of the MFCC extraction $\alpha = 0.42$ were

used a pre-emphasis coefficient. The PyWORLD vocoder also provides the F_0 and BAP values for synthesis, these were explicitly given for the synthesis, due to the reasons stated in the Introduction.

2.5. Delay

Previously [8], the effect of delay on the output signal were investigated. While it has been found that delay is beneficial, the author's choice of function approximators are restricted to acausal models, so it has been decided not to use delay in our final implementation.

2.6. Fundamental frequency interpolation

Previously, it has been found beneficial to take the logarithm of the pitch to obtain a continuous F_0 curve. When the logarithm is not defined, linear interpolation has been done. [5] An alternative method also exists with exponential interpolation which is described in [9]. It has been decided that the linear interpolation technique will be used.

2.7. Normalisation

Exploratory data analysis indicated that the articulatory trajectories of the datasets were on different scale and bias, so it was normalised on a per speaker basis. The output MFCCs were normalised for each cepstral coefficients.

2.8. Neural network

To approximate the functional relationship, the authors have decided to train a Bidirectional Long-Short Term Memory based neural network [10].

For all BLSTM layers, the CuDNNLSTM implementation have been used to improve efficiency, however this limits the activation function to be strictly $\tanh(\cdot)$.

A LSTM is governed by the following equations,

$$\mathbf{i}_t = \sigma(\mathbf{W}_{xi}\mathbf{x}_t + \mathbf{W}_{hi}\mathbf{h}_{t-1} + \mathbf{W}_{ci}\mathbf{c}_{t-1} + \mathbf{b}_i), \quad (1)$$

$$\mathbf{f}_t = \sigma(\mathbf{W}_{xf}\mathbf{x}_t + \mathbf{W}_{hf}\mathbf{h}_{t-1} + \mathbf{W}_{cf}\mathbf{c}_{t-1} + \mathbf{b}_f), \quad (2)$$

$$\mathbf{c}_t = \mathbf{f}_t\mathbf{c}_{t-1} + \mathbf{i}_t\tanh(\mathbf{W}_{hc}\mathbf{h}_{t-1} + \mathbf{b}_c), \quad (3)$$

$$\mathbf{o}_t = \sigma(\mathbf{W}_{xo}\mathbf{x}_t + \mathbf{W}_{ho}\mathbf{h}_{t-1} + \mathbf{W}_{co}\mathbf{c}_t + \mathbf{b}_o), \quad (4)$$

$$\mathbf{h}_t = \mathbf{o}_t\tanh(\mathbf{c}_t). \quad (5)$$

The exact architectures are described in the Section 3.1.

2.9. Synthesis

Synthesis for the validation set is performed using the ground truth parameters for the BAP and F_0 and only the spectral prediction is benchmarked.

3. Experiment

3.1. Neural network experiments

Three recurrent neural networks architectures were trained based on previous papers tackling similar problems.

Based on [4], a bidirectional LSTM was trained with four layers. The final layer was a fully connected layer matching the output dimensions. This neural network was trained using stochastic gradient descent and a learning rate of $\alpha = 0.01$.

Another publication [3] used a neural networks with three fully connected layers with 128 hidden units, each layer has

Table 2: Comparison of preprocessing techniques

Author	Liu	Taguchi	Gonzalez
EMA/PMA	EMA	EMA	PMA
MFCC	40 + 1	40 + 1	24 + 1
Delta	No	Yes	Yes
EMA sampling	200 Hz	200 Hz	100 Hz*
Input standardisation	Yes	N/A	Yes
Trajectory smoothing	No	Yes	No
Output standardisation	Yes	Yes	Yes
Vocoder	STRAIGHT	WORLD	STRAIGHT

*Upsampled to 200 to match analysis rate

a linear activation function, which is followed by Layer Normalisation and a sigmoid activation function. This is followed by two BLSTM layers with 256 hidden units. Finally, a fully connected layer is used. This neural network was trained using Grave’s RMSProp (TODO: ref), with a learning rate of $\alpha = 0.01$.

Finally, another BLSTM was trained based on the architecture of [4], but using Adam as an optimiser [11].

Determining a good set of architecture and parameter settings is the most difficult part of the experiment design. Bidirectional LSTMs have performed the best on predicting the MFCC spectra in all related papers. Taguchi uses fully-connected layers and while it not justified in the paper, it is reasonable to assume that this does pre-processing of the time-series.

It can be easily seen mathematically that after the last LSTM layer, a fully connected layer is also needed as this acts as a linear regression based on the LSTM parameters. This is because the range of the activation function is not sufficient to capture the range of the normalised MFCCs. It is possible to introduce some structural bias by using the same linear regression from each frame, somewhat limiting complexity.

In terms of the optimisation, Adam and Graves’s RMSProp is preferred, which is not surprising due to the fact that these known to be better for optimising non-stationary objectives. With the SGD, finicky learning rate scheduling had to be used.

Table 3: Comparison of different training methods

Author	Liu	Taguchi	Gonzalez
BLSTM layers	4 (128)	2 (256)	4 (150) GRU
Dense layers	1	3+1	1
Regularisation	No	LayerNorm	Noise 0.05
Dropout	No	Yes (50 %)	No
Optimiser	SGD	Grave’s RMSProp	Adam
Learning rate	0.01*	0.01	0.003
Gradient clipping	No	5	No
Early stopping	Yes	Yes	Yes
MLPG	Yes	No	Yes
Maximum epochs	32	N/A	100
Batch size	N/A	8	100
Incremental training	No	Yes	Yes

* with decay after Epoch 11

** from author communication

For training the mean squared error loss function was used, and for evaluation the Mel cepstral distortion (MCD) have been employed. [12]

Ten fold cross-validation was performed to estimate the out-of-sample generalisation capability of the neural networks.

Table 4: Comparison of different training methods

Architecture	Optimiser	Base learning rate
Liu 2018	SGD	0.01
Taguchi 2018	RMSProp	0.01
Modified Liu	Adam	0.01

3.2. Pathological speech synthesis

Pathological speech synthesis is performed by considering the articulatory space and taking knowledge about the change of articulation.

In tongue cancer, articulation of the tongue is impeded. In practice, it is found that teaching patients to speak at a slower rate helps these articulation problems. Thus, it is hypothesised that is the maximum velocity of the tongue that is limited in pathological speech.

A pathological speech transformation could then be constructed for a discretet time signal by first taking the discrete time difference,

$$d[t] = x[t] - x[t - 1], \quad (6)$$

where $x[t] \in \mathbb{R}^T$ is a signal for one particular electrode channel.

The difference signal then can be thresholded using,

$$d_p[t] = \min(d[t], c) \quad \text{for } d[t] \geq 0, \quad (7)$$

$$d_p[t] = \min(d[t], -c) \quad \text{for } d[t] < 0, \quad (8)$$

where $c \in \mathbb{R}^+$ is a positive number representing an arbitrary threshold.

After obtaining this signal a cumulative sum could be performed to obtain the pathological EMA signal

$$p[t] = \sum_{i=0}^t x[i]. \quad (9)$$

This signal then could be fed through a feedforward run of a neural network to synthesise pathological speech.

4. Results and discussion

4.1. Benchmark results

Table 5: Comparison of 10-fold CV performance of neural networks

Architecture	MCD
Liu 2018	5.8 dB
Taguchi 2018	6.2 dB
Modified Liu	6 dB

It is important to note that the original networks were trained on single speakers, that is why the MCD values are higher than in the original publications.

4.2. Learning curves

The training set was increased from ten percent of it’s total size to it’s total size in increments of ten percents, and the mean

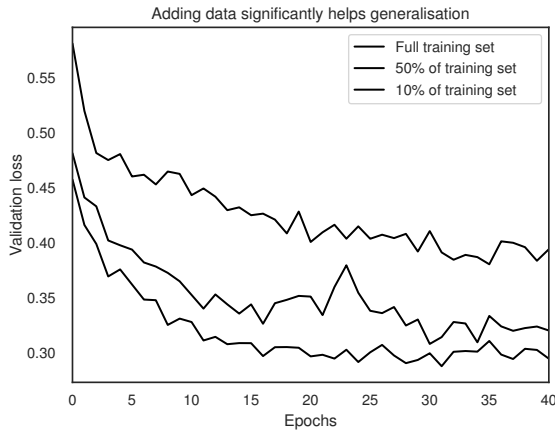


Figure 3: Partial data retraining shows that adding more data would decrease loss

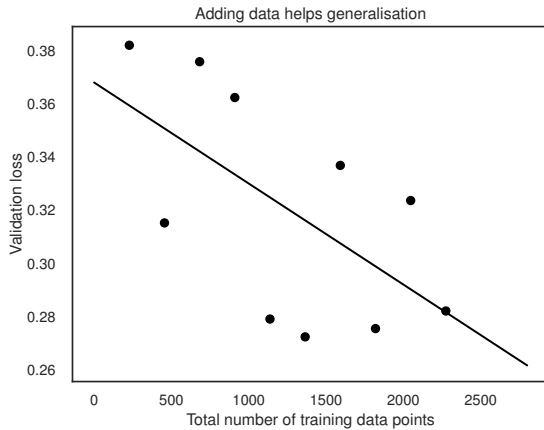


Figure 4: Partial data retraining shows that adding more data would decrease loss.

squared error was calculated at all epochs of training for the validation set, which can be seen on Figure 3.

After that, a paired t-test was performed to answer whether there is a statistically significant improvement with each addition of the training data. It has been found that for each addition, the paired t-test resulted in statistically significant results, which indicates that it is very likely that addition of more data improves the model.

To estimate how much data would be needed to achieve a "perfect" performance, assuming a linear fit, the mean of the validation loss in last 5 epochs were taken and regressed against the amount of training data included in number of samples. This fit can be seen on Figure 4. Taking the ratio of the slope and the intercept, approximately 8382 training data point would be needed.

Again, note that there are several limitations of this assumption. First, the relationship is most likely not linear. Secondly, given any noise, achieving zero loss is impossible. However, these benchmarks still have merit in future experiment design.

4.3. Pathological speech examples

The pathological speech examples can be listened on the webpage of the author, see <http://karkiowle.github.io/paper1>.

5. Conclusion

This paper is a proof of concept that it is possible to make pathological speech by incorporating changes in an articulatory domain. Benchmarks have been also established and an open source repository is also available in order to reproduce these results. Using cross-validation as the training data increases, bounds have been established on the expected amount of data needed for the model to improve.

It can be concluded that it is possible to make satisfactory quality speech synthesis, and it is possible to present some lisping pathologies.

In future work, changes in articulation during oral cancer will be investigated using oral cancer to use empirical data for speech synthesis instead of physical considerations.

6. Acknowledgements

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7. References

- [1] J. Benesty, M. M. Sondhi, Y. Huang, and S. Greenberg, *Springer Handbook of Speech Processing*, 2009, vol. 126, no. 4. [Online]. Available: <http://scitation.aip.org/content/asa/journal/jasa/126/4/10.1121/1.3203918>
- [2] S. Aryal and R. Gutierrez-Osuna, "Data driven articulatory synthesis with deep neural networks," *Computer Speech and Language*, vol. 36, pp. 260–273, 2016. [Online]. Available: <http://dx.doi.org/10.1016/j.csl.2015.02.003>
- [3] F. Taguchi and T. Kaburagi, "Articulatory-to-speech conversion using bi-directional long short-term memory." [Online]. Available: https://www.isca-speech.org/archive/Interspeech{_}2018/pdfs/0999.pdf
- [4] Z. C. Liu, Z. H. Ling, and L. R. Dai, "Articulatory-to-acoustic conversion using BLSTM-RNNs with augmented input representation," *Speech Communication*, vol. 99, no. February, pp. 161–172, 2018. [Online]. Available: <https://doi.org/10.1016/j.specom.2018.02.008>
- [5] J. A. Gonzalez, L. A. Cheah, P. D. Green, J. M. Gilbert, S. R. Ell, R. K. Moore, and E. Holdsworth, "Evaluation of a silent speech interface based on magnetic sensing and deep learning for a phonetically rich vocabulary," *Proceedings of the Annual Conference of the International Speech Communication Association, INTERSPEECH*, vol. 2017-August, pp. 3986–3990, 2017.
- [6] K. Richmond, P. Hoole, and S. King, "Announcing the electromagnetic articulography (day 1) subset of the mngu0 articulatory corpus," in *Proceedings of the Annual Conference of the International Speech Communication Association, INTERSPEECH*, 2011.
- [7] M. Morise, F. Yokomori, and K. Ozawa, "WORLD: A vocoder-based high-quality speech synthesis system for real-time applications," *IEICE Transactions on Information and Systems*, 2016.
- [8] J. A. Gonzalez, L. A. Cheah, J. M. Gilbert, J. Bai, S. R. Ell, P. D. Green, and R. K. Moore, "A silent speech system based on permanent magnet articulography and direct synthesis," *Computer Speech and Language*, 2016.

- [9] C. J. Chen, R. A. Gopinath, M. D. Monkowski, M. A. Picheny, and K. Shen, "New methods in continuous Mandarin speech recognition." *5th European Conference on Speech Communication and Technology (EUROSPEECH)*, 1997.
- [10] S. Hochreiter and J. Schmidhuber, "Long Short-Term Memory," *Neural Computation*, 1997.
- [11] D. P. Kingma and J. L. Ba, "Adam: A method for stochastic gradient descent," *ICLR: International Conference on Learning Representations*, 2015.
- [12] R. F. Kubichek, "Mel-cepstral Distance Measure for Objective Speech Quality Assessment," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing*, pp. 125–128, 1993.