Generative modeling of speech F_0 contours

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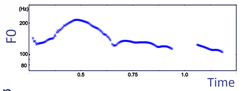
Abstract: This paper reviews our ongoing work on generative modeling of speech fundamental frequency (F_0) contours for estimating prosodic features from raw speech data [3]-[6]. Proposed F_0 contour model is formulated by translating "Fujisaki model" into probabilistic model described as discrete-time stochastic process. The motivation behind this formulation is:

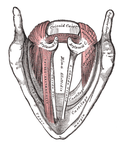
① to derive a general parameter estimation framework for Fujisaki model, allowing for introduction of powerful statistical methods

② to construct an automatically trainable version of Fujisaki model so that in future it can be incorporated into statistical-model-based text-to-speech synthesis systems

1. Introduction



- Fundamental frequency (F_0) contour
  - time course of frequency of vocal fold vibration (Manifestation of physical movement of thyroid cartilage)
  - contains various types of non-linguistic information
    - Speaker's identity, intention, attitude, mood, etc.
  - modeling and analyzing F_0 contours can be potentially useful for many speech applications in which prosodic information plays a significant role. (In speech synthesis, one challenge is to create a natural -sounding pitch contour for the utterance as a whole.)

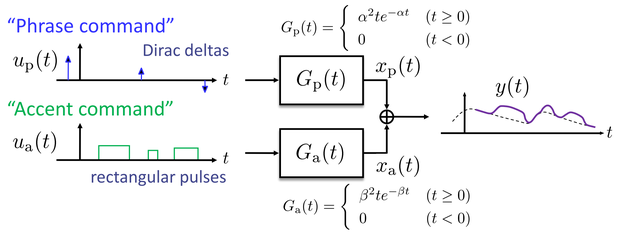


- "Fujisaki model" [1]
  - F_0 contour typically consists of two components:
    - **phrase components** (long term pitch variations over the duration of prosodic units), and
    - **accent components** (short term pitch variations in accented syllables).

    "Fujisaki model" is a well-founded mathematical model that describes F0 contour as the sum of these two components (See below for details).
  - A notable feature of this model is that the model parameters are associated with physiologically and linguistically meaningful quantities.
  - However, automatic estimation of Fujisaki model parameters from raw F_0 contour has been a difficult task...
- Aim of this paper
  - **translate Fujisaki model into a probabilistic model (stochastic process)**
  - motivation for this is twofold:
    - to provide general parameter estimation framework utilizing powerful statistical inference methods, and
    - to construct an automatically trainable version of Fujisaki model that can potentially be combined with statistical model for speech synthesis.

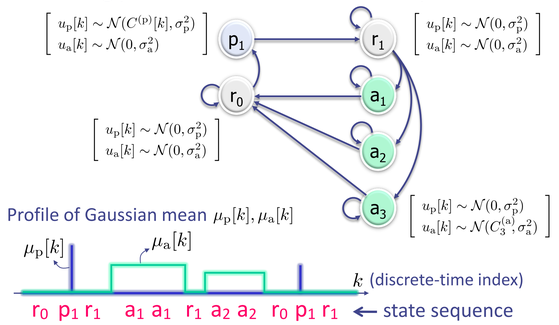
2. Original Fujisaki model [1]

- Fujisaki model assumes:
  - F_0 contour (log scale) = Phrase component + Accent component + Base value (lower bound for F_0)
    - contributions associated with forward-backward translation and rotation of thyroid cartilage, respectively
    - outputs of different 2nd order critically damped systems



3. Generative model of speech F_0 contours

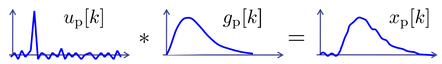
- Generative modeling of phrase and accent commands
  - Requirements
    - Phrase command is impulse
    - Accent command is rectangular pulse
    - Two commands do not overlap each other
  - Propose introducing path-restricted HMM for modeling phrase & accent command sequence



state transition: $s_k | s_{k-1} \sim \pi_{s_{k-1}, s_k}$

state emission: $\begin{bmatrix} u_p[k] \\ u_a[k] \end{bmatrix} | s_k \sim \mathcal{N}\left(\begin{bmatrix} \mu_p[k] \\ \mu_a[k] \end{bmatrix}, \begin{bmatrix} \sigma_p^2 & 0 \\ 0 & \sigma_a^2 \end{bmatrix} \right)$

- Generative modeling of F_0 contour
  - Relationship between $u_p[k]$ and $x_p[k]$



$$\underbrace{\begin{bmatrix} u_p[1] \\ u_p[2] \\ \vdots \\ u_p[K] \end{bmatrix}}_{\boldsymbol{u}_p} = \underbrace{\begin{bmatrix} f_0^{(p)} & & & O \\ f_1^{(p)} & f_0^{(p)} & & \\ f_2^{(p)} & f_1^{(p)} & f_0^{(p)} & \\ & \ddots & \ddots & \ddots \\ O & & f_2^{(p)} & f_1^{(p)} & f_0^{(p)} \end{bmatrix}}_{\boldsymbol{F}_p} \underbrace{\begin{bmatrix} x_p[1] \\ x_p[2] \\ \vdots \\ x_p[K] \end{bmatrix}}_{\boldsymbol{x}_p}$$

  - Relationship between $u_a[k]$ and $x_a[k]$

$$\boldsymbol{u}_a = \boldsymbol{F}_a \boldsymbol{x}_a$$

  - Probability density function of $x_p[k]$ and $x_a[k]$

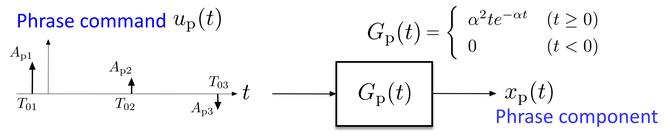
$$\boldsymbol{x}_p | s_1, \ldots, s_K \sim \mathcal{N}(\boldsymbol{F}_p^{-1}\boldsymbol{\mu}_p, \boldsymbol{F}_p^{-1}\boldsymbol{\Sigma}_p\boldsymbol{F}_p^{-\mathsf{T}})$$
$$\boldsymbol{x}_a | s_1, \ldots, s_K \sim \mathcal{N}(\boldsymbol{F}_a^{-1}\boldsymbol{\mu}_a, \boldsymbol{F}_a^{-1}\boldsymbol{\Sigma}_a\boldsymbol{F}_a^{-\mathsf{T}})$$

  - Probability density function of $y[k]$

$$\boldsymbol{y} | \boldsymbol{s} \sim \mathcal{N}(\boldsymbol{F}_p^{-1}\boldsymbol{\mu}_p + \boldsymbol{F}_a^{-1}\boldsymbol{\mu}_a + \mu_b \mathbf{1}, \boldsymbol{F}_p^{-1}\boldsymbol{\Sigma}_p\boldsymbol{F}_p^{-\mathsf{T}} + \boldsymbol{F}_p^{-1}\boldsymbol{\Sigma}_p\boldsymbol{F}_p^{-\mathsf{T}} + \boldsymbol{\Sigma}_b)$$

Discretized Fujisaki model

- Discretization of phrase control mechanism



  - 2nd order critically damped filter (Laplace domain): $\alpha^2/(s+\alpha)^2$
  - Inverse filter (Laplace domain): $(s+\alpha)^2/\alpha^2$

Backward difference approximation $s = \dfrac{1 - z^{-1}}{t_0}$ (Sampling period)

  - Inverse filter (z-domain):

$$\frac{z^{-2} - 2(\alpha t_0 + 1)z^{-1} + (\alpha t_0 + 1)^2}{\alpha^2 t_0^2}$$

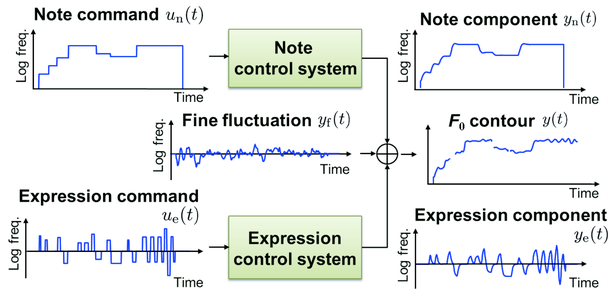
$$u_p[k] = f_0^{(p)} x_p[k] + f_1^{(p)} x_p[k-1] + f_2^{(p)} x_p[k-2]$$
where $f_0^{(p)} = (\psi - 1)^2$, $f_1^{(p)} = -2\psi(\psi - 1)$, $f_2^{(p)} = \psi^2$

Constrained all-pole model governed by single parameter $\psi = 1 + 1/(\alpha t_0)$

- Discretization of accent control mechanism
  - follows exactly the same as above

4. Singing voice F_0 contour modeling [6]

- Propose describing singing voice F_0 contour based on a model structurally similar to Fujisaki model



- This model can be translated into a probabilistic model in the same way as above.

5. MAP estimation

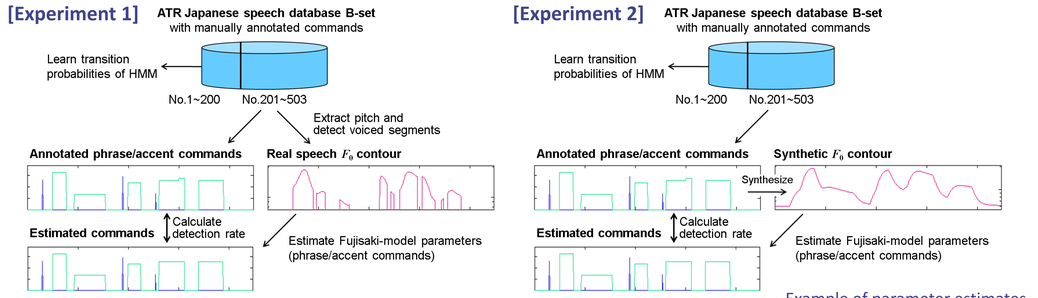
- Maximum A Posteriori estimation of Fujisaki model parameters (namely, state sequence of present HMM)

$$\hat{\boldsymbol{s}} = \underset{\boldsymbol{s}}{\operatorname{argmax}} \log p(\boldsymbol{s}|\boldsymbol{y}) = \underset{\boldsymbol{s}}{\operatorname{argmax}} \log p(\boldsymbol{y}|\boldsymbol{s}) p(\boldsymbol{s})$$

(observed F_0 contour)

  - Likelihood function: $p(\boldsymbol{y}|\boldsymbol{s}) = \mathcal{N}(\boldsymbol{F}_p^{-1}\boldsymbol{\mu}_p + \boldsymbol{F}_a^{-1}\boldsymbol{\mu}_a + \mu_b \mathbf{1}, \boldsymbol{F}_p^{-1}\boldsymbol{\Sigma}_p\boldsymbol{F}_p^{-\mathsf{T}} + \boldsymbol{F}_p^{-1}\boldsymbol{\Sigma}_p\boldsymbol{F}_p^{-\mathsf{T}} + \boldsymbol{\Sigma}_b)$
  - Prior distribution: $p(\boldsymbol{s}) = \pi_{s_1} \prod_{k=2}^{K} \pi_{s_{k-1}, s_k}$
- Developed Iterative algorithm for estimating $\hat{\boldsymbol{s}}$ based on EM algorithm
  - See [3]-[6] for details.

5. Evaluation using real/synthetic data



- Results

[Experiment 1]

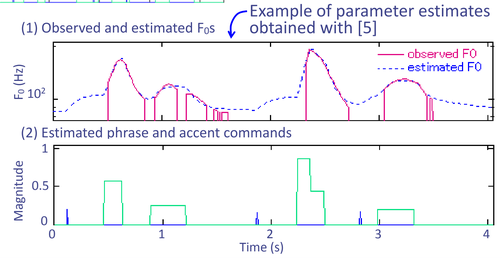
	DR (%)	RMSE
Conventional [2]	68.8	0.1719
Proposed1 [4]	69.7	0.1372
Proposed2 [5]	69.5	0.0611

[Experiment 2]

	DR (%)
Conventional [2]	72.6
Proposed1 [4]	76.8
Proposed2 [5]	83.4

DR: Detection rate
"RMSE": RMSE between observed F_0 contour and optmized model

Example of parameter estimates obtained with [5]



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