Applying Base Value of the Fundamental Frequency via Multivariate Kernel-Density in Forensic Speaker Comparison

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Outline

- Motivation
- Application of a single LTF0 parameter
- Application of combined LTF0 parameters
- Proposed combination of the LTF0 parameters
- Conclusions
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Motivation (1)

- Master course in forensic computer science at University of Brasília (UnB)
  - Transference of financial resources from Brazilian Federal Police to UnB
  - 30 forensic experts concluding their master course until Dec. 2016
- Increase of digital medias with crimes: audios from whatsapp
- Forensic Speaker Comparison (FSC)
  - Comparison between the speech of an offender and the speech of a suspect: criminal conviction or proof of innocence of the suspect
- Several tools for voice recognition
  - Commercial solution based on MFCC GMM: Batvox
  - Fundamental frequency (F0)
Motivation (2)

- acoustic parameter used most in FSC due to its simplicity and robustness in poor quality audio recordings
- Base value of F0 (F_b): less affected by the speech style, the content, the recording channel and the speaker effort [1,2]

**Forensic Speaker Comparison by the Federal Police**

- Yearly: 200 requests, however only 60 performed procedures
- Methodology based on perceptual and acoustic analysis: subjectivity
  - European Network of Forensic Science Institutes (ENFSI)
    - Reproducibility and scientific basis
- 30 days of work for the voice analysis by a forensic expert


Motivation (3)

- Usage of the long term fundamental frequency (LTF0) in FSC by forensic experts [3]
  - 94% of forensic experts: arithmetic mean ($\mu$) of F0
  - 72% of forensic experts: standard deviation ($\sigma$) of F0
  - 41% of forensic experts: median ($\hat{Q}_2$) of F0
  - 34% of forensic experts: mode ($\hat{\phi}$) of F0
  - 25% of forensic experts: base value ($\hat{F}_b$) of F0

- Proposal: combination of the base value of F0 with other statistical long-term measures of F0 using the Multivariate Kernel Density (MVKD)
  - Smallest error metrics by combining the base value ($\hat{F}_b$) and the median ($\hat{Q}_2$) of F0

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Single Long Term Fundamental Frequency Parameter (LTF0) (1)

- Fundamental frequency (F0)
  - Number of complete cycles of opening and closing the vocal cords per second
  - Time series and spectrogram using Praat: 35 values for F0
Single Long Term Fundamental Frequency Parameter (LTF0) (2)

- Base value of F0 ($F_b$)
  - personal vocal cords frequency [4]
  - carrier frequency: composed of the linguistic and extra-linguistic components
  - $F_b = \mu - 1.43\sigma$
  - 7.64 % percentile of the F0 distribution

Most used long term fundamental frequency (LTF0) in forensics

<table>
<thead>
<tr>
<th>LTF0</th>
<th>Code</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic mean</td>
<td>LTF0₁</td>
<td>$\bar{\mu}$</td>
</tr>
<tr>
<td>Median</td>
<td>LTF0₂</td>
<td>$\hat{Q}_2$</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>LTF0₃</td>
<td>$\hat{\sigma}$</td>
</tr>
<tr>
<td>Base value of F0</td>
<td>LTF0₄</td>
<td>$\hat{F}_b$</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>LTF0₅</td>
<td>$\hat{\omega}$</td>
</tr>
<tr>
<td>Skewness</td>
<td>LTF0₆</td>
<td>$\hat{\eta}$</td>
</tr>
<tr>
<td>Mode</td>
<td>LTF0₇</td>
<td>$\hat{\phi}$</td>
</tr>
<tr>
<td>Modal Density</td>
<td>LTF0₈</td>
<td>$\hat{\gamma}$</td>
</tr>
</tbody>
</table>
Corpus:

- Forensic Brazilian Portuguese Corpus (CFPB)
  - 206 male and 50 female studio quality speaker recordings including semi-spontaneous speaking (interview) and reading sentences
  - Each recording with five minute duration of a net semi-spontaneous speech and two minute duration of reading
  - Validation with subset of 206 semi-spontaneous male recordings of the CFPB from all regions of Brazil
    - More than 90 % of the crimes with male recordings
Trace with \( R \) recordings

Suspect’s model with \( R \) recordings

Contour (voice activity) of \( R \) traces and \( R \) recordings

\( S \) sections each with \( t_s \) seconds: typically 5 s to 2 min

For each section (with voice activity) of each part, computation of eight long term fundamental frequency parameters (LTF0)
Single Long Term Fundamental Frequency Parameter (LTF0) (6)

- $R \times R$ comparisons for each section and for each LFT0

\[
\begin{pmatrix}
LR_{1,1} & LR_{1,2} & \cdots & LR_{1,R} \\
LR_{2,1} & LR_{2,2} & \cdots & LR_{2,R} \\
\vdots & \vdots & \ddots & \vdots \\
LR_{R,1} & LR_{R,2} & \cdots & LR_{R,R}
\end{pmatrix}
\]

- Likelihood Ratio (LR) matrix with all $R \times R$ comparisons
- Same speaker comparisons in the main diagonal ($r_1 = r_2$)
Likelihood Ratio (LR)

<table>
<thead>
<tr>
<th>$\log_{10}(LR)$</th>
<th>Verbal expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log_{10}(LR) \geq 4$</td>
<td>Very strong evidence support to same source</td>
</tr>
<tr>
<td>$3 \leq \log_{10}(LR) &lt; 4$</td>
<td>Strong evidence support to same source</td>
</tr>
<tr>
<td>$2 \leq \log_{10}(LR) &lt; 3$</td>
<td>Moderately strong evidence support to same source</td>
</tr>
<tr>
<td>$1 \leq \log_{10}(LR) &lt; 2$</td>
<td>Moderate evidence support to same source</td>
</tr>
<tr>
<td>$0 &lt; \log_{10}(LR) &lt; 1$</td>
<td>Limited evidence support to same source</td>
</tr>
<tr>
<td>$\log_{10}(LR) = 0$</td>
<td>No evidence support</td>
</tr>
<tr>
<td>$-1 &lt; \log_{10}(LR) &lt; 0$</td>
<td>Limited evidence support to different source</td>
</tr>
<tr>
<td>$-2 &lt; \log_{10}(LR) \leq -1$</td>
<td>Moderate evidence support to different source</td>
</tr>
<tr>
<td>$-3 &lt; \log_{10}(LR) \leq -2$</td>
<td>Moderately strong evidence support to different source</td>
</tr>
<tr>
<td>$-4 &lt; \log_{10}(LR) \leq -3$</td>
<td>Strong evidence support to different source</td>
</tr>
<tr>
<td>$\log_{10}(LR) \leq -4$</td>
<td>Very strong evidence support to different source</td>
</tr>
</tbody>
</table>
Computation of the LR for comparisons of all traces against all suspect’s models

EER metrics

Equal Error Rate (EER)
- Adjust point that FAR = FRR
- False Acceptance Rate (FAR)
- False Rejection Rate (FRR)
- Decision threshold $\delta$ for the LR

\[
\text{FRR}(\mathcal{K}, \delta, s) = \frac{1}{2 \cdot R} \sum_{r_1=r_2=1}^{R} \left[ \text{sign}(\delta - m_{\mathcal{K}, r_1, r_2, s}) + 0.5 \right]
\]

\[
\text{FAR}(\mathcal{K}, \delta, s) = \frac{1}{2 \cdot R(R-1)} \sum_{r_1=1}^{R} \sum_{r_2=1}^{R} \left[ \text{sign}(m_{\mathcal{K}, r_1, r_2, s} - \delta) + 0.5 \right]
\]

\[
\text{EER}(\mathcal{K}, s) = \min |\text{FAR}(\mathcal{K}, \delta, s) - \text{FRR}(\mathcal{K}, \delta, s) |
\]
Single Long Term Fundamental Frequency Parameter (LTF0): reproduction of results using the CFPB forensic corpus (1)

<table>
<thead>
<tr>
<th>LTF0 (Symbol)</th>
<th>$t_s = 5s$</th>
<th>$t_s = 10s$</th>
<th>$t_s = 15s$</th>
<th>$t_s = 20s$</th>
<th>$t_s = 30s$</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTF0_4 ($\hat{F}_b$)</td>
<td>16.5</td>
<td>15.9</td>
<td>16.1</td>
<td>16.1</td>
<td>15.7</td>
<td><strong>16.1</strong></td>
</tr>
<tr>
<td>LTF0_1 ($\hat{\mu}$)</td>
<td>22.3</td>
<td>22.2</td>
<td>22.0</td>
<td>21.9</td>
<td>21.4</td>
<td><strong>22.0</strong></td>
</tr>
<tr>
<td>LTF0_7 ($\hat{\psi}$)</td>
<td>22.2</td>
<td>20.9</td>
<td>22.1</td>
<td>21.7</td>
<td>23.3</td>
<td><strong>22.0</strong></td>
</tr>
<tr>
<td>LTF0_2 ($\hat{Q}_2$)</td>
<td>22.3</td>
<td>21.8</td>
<td>22.7</td>
<td>21.7</td>
<td>21.5</td>
<td><strong>22.0</strong></td>
</tr>
<tr>
<td>LTF0_3 ($\hat{\sigma}$)</td>
<td>32.0</td>
<td>32.5</td>
<td>32.5</td>
<td>33.0</td>
<td>33.0</td>
<td><strong>32.6</strong></td>
</tr>
<tr>
<td>LTF0_8 ($\hat{\gamma}$)</td>
<td>33.4</td>
<td>33.0</td>
<td>32.5</td>
<td>33.1</td>
<td>34.0</td>
<td><strong>33.2</strong></td>
</tr>
<tr>
<td>LTF0_6 ($\hat{\eta}$)</td>
<td>45.2</td>
<td>42.1</td>
<td>40.3</td>
<td>43.7</td>
<td>41.9</td>
<td><strong>42.6</strong></td>
</tr>
<tr>
<td>LTF0_5 ($\hat{w}$)</td>
<td>42.0</td>
<td>43.7</td>
<td>41.7</td>
<td>42.2</td>
<td>43.1</td>
<td><strong>42.5</strong></td>
</tr>
<tr>
<td>Mean</td>
<td>29.5</td>
<td>29.0</td>
<td><strong>28.7</strong></td>
<td>29.2</td>
<td>29.2</td>
<td><strong>29.1</strong></td>
</tr>
</tbody>
</table>
Single Long Term Fundamental Frequency Parameter (LTF0): reproduction of results using the CFPB forensic corpus (2)

- Detection Error Tradeoff (DET) curves of the isolated LTF0 parameters

- 94% of forensic experts: arithmetic mean ($\hat{\mu}$) of $F_0$
- 72% of forensic experts: standard deviation ($\hat{\sigma}$) of $F_0$
- 41% of forensic experts: median ($\hat{Q}_2$) of $F_0$
- 34% of forensic experts: mode ($\hat{\phi}$) of $F_0$
- 25% of forensic experts: base value ($\hat{F}_b$) of $F_0$

$\hat{F}_b$: low frequency ranges
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Likelihood Ratios (LR) of the combined LFT0 parameters
- Multivariate Kernel-Density (MVKD) function proposed in [5]

MVKD
- Computation of the LR in acoustic-phonetic parameters [6]
- Applied for variables for small amount of samples
- Exploitation of the statistical dependence between the variables


Combined Long Term Fundamental Frequency Parameters (LTF0) (1)

- MVKD of the Likelihood Ratios (LRs)

 Dependence on the chosen metrics, e.g., EER

\[ 2 \leq \log_{10}(LR) < 3 \quad | \quad \text{Moderately strong evidence support to same source} \]

Normalized histogram
Combined Long Term Fundamental Frequency Parameters (LTF0): reproduction of results using a forensic corpus (1)

State-of-the-art combinations of the LTF0 parameters

<table>
<thead>
<tr>
<th>LTF0 {κ}</th>
<th>EER (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_s = 5s$</td>
</tr>
<tr>
<td>κ = {1, 3, 5, 6, 7, 8} = [7]</td>
<td>15.4</td>
</tr>
<tr>
<td>κ = {1, 3} = [8]</td>
<td>17.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LTF0</th>
<th>Code</th>
<th>Symbol</th>
</tr>
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<tbody>
<tr>
<td>Arithmetic mean</td>
<td>LTF0(_1)</td>
<td>$\hat{\mu}$</td>
</tr>
<tr>
<td>Median</td>
<td>LTF0(_2)</td>
<td>$\hat{Q}_2$</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>LTF0(_3)</td>
<td>$\hat{\sigma}$</td>
</tr>
<tr>
<td>Base value of F0</td>
<td>LTF0(_4)</td>
<td>$\hat{F}_b$</td>
</tr>
<tr>
<td>Kurtosis</td>
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<td>Skewness</td>
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<tr>
<td>Mode</td>
<td>LTF0(_7)</td>
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</tr>
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<td>Modal Density</td>
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</tr>
</tbody>
</table>

• Not combined to other LTF0

Our goal: propose combinations of the LTF0 to reduce the EER and CLLR
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Proposed combined LTF0 (1)

- EER of the proposed combination of the LTF0 Parameters

<table>
<thead>
<tr>
<th>LTF0 {Κ}</th>
<th>$t_s = 5s$</th>
<th>$t_s = 10s$</th>
<th>$t_s = 15s$</th>
<th>$t_s = 20s$</th>
<th>$t_s = 30s$</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Κ = {2, 4}$</td>
<td>14.9</td>
<td>14.2</td>
<td><strong>13.0</strong></td>
<td>14.6</td>
<td>13.5</td>
<td>14.0</td>
</tr>
<tr>
<td>$Κ = {2, 4, 7}$</td>
<td>14.9</td>
<td>14.1</td>
<td>13.1</td>
<td>14.5</td>
<td>13.7</td>
<td>14.1</td>
</tr>
<tr>
<td>$Κ = {1, 2, 4}$</td>
<td>15.4</td>
<td>14.5</td>
<td>13.5</td>
<td>14.0</td>
<td>13.6</td>
<td>14.2</td>
</tr>
<tr>
<td>$Κ = {1, 2, 4, 7}$</td>
<td>14.6</td>
<td>15.0</td>
<td><strong>13.2</strong></td>
<td>14.9</td>
<td>14.5</td>
<td>14.4</td>
</tr>
<tr>
<td>$Κ = {1, 4}$</td>
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<td>15.1</td>
</tr>
<tr>
<td>$Κ = {4, 7}$</td>
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<td>14.6</td>
<td>14.6</td>
<td>16.1</td>
<td>15.5</td>
<td>15.1</td>
</tr>
<tr>
<td>$asmus = {1, 3, 5, 6, 7, 8} = [7]$</td>
<td>15.4</td>
<td>15.0</td>
<td>14.6</td>
<td>14.5</td>
<td>14.4</td>
<td>14.8</td>
</tr>
<tr>
<td>$Κ = {1, 3, 4, 5, 6, 7, 8} = [7]+\hat{F}_b$</td>
<td>14.0</td>
<td>14.2</td>
<td>15.1</td>
<td>14.5</td>
<td>15.1</td>
<td>14.6</td>
</tr>
<tr>
<td>$Κ = {1, 3} = [8]$</td>
<td>17.4</td>
<td>17.3</td>
<td>17.5</td>
<td>17.0</td>
<td>17.0</td>
<td>17.2</td>
</tr>
<tr>
<td>$Κ = {1, 2, 3, 4, 5, 6, 7, 8}$</td>
<td>15.1</td>
<td>15.0</td>
<td>15.4</td>
<td>15.0</td>
<td>15.1</td>
<td>15.1</td>
</tr>
</tbody>
</table>
Proposed combined LTF0 (2)

- DET curves of the combined LTF0 parameters

![DET curves of the combined LTF0 parameters]

<table>
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<tr>
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<tr>
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</tr>
<tr>
<td>Modal Density</td>
<td>LTF0₈</td>
<td>$\hat{\gamma}$</td>
</tr>
</tbody>
</table>
Proposed combined LTF0 (3)

- Log-likelihood-ratio cost ($C_{llr}$) metrics [9]

$$C_{llr}(\mathcal{K}, s) = \frac{1}{2} \left( \frac{1}{R} \sum_{i=1}^{R} \log_2 \left[ 1 + \frac{1}{LR_{ss}} \right] + \frac{1}{(R(R-1))} \sum_{j=1}^{R(R-1)} \log_2 \left[ 1 + LR_{ds} \right] \right)$$


Proposed combined LTF0 (4)

- Cllr of the LTF0 combinations applied to the CFPB corpus

<table>
<thead>
<tr>
<th>LTF0 ${\mathcal{K}}$</th>
<th>$t_s = 5s$</th>
<th>$t_s = 10s$</th>
<th>$t_s = 15s$</th>
<th>$t_s = 20s$</th>
<th>$t_s = 30s$</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{K} = {2, 4}$</td>
<td>0.685</td>
<td>0.621</td>
<td><strong>0.618</strong></td>
<td>0.642</td>
<td>0.849</td>
<td>0.683</td>
</tr>
<tr>
<td>$\mathcal{K} = {2, 4, 7}$</td>
<td>0.950</td>
<td>0.952</td>
<td>0.743</td>
<td>0.952</td>
<td>1.113</td>
<td>0.940</td>
</tr>
<tr>
<td>$\mathcal{K} = {1, 2, 4}$</td>
<td>0.950</td>
<td>0.952</td>
<td>0.920</td>
<td>0.953</td>
<td>1.113</td>
<td>0.978</td>
</tr>
<tr>
<td>$\mathcal{K} = {1, 2, 4, 7}$</td>
<td>0.916</td>
<td>0.900</td>
<td>1.151</td>
<td>0.810</td>
<td>0.984</td>
<td>0.952</td>
</tr>
<tr>
<td>$\mathcal{K} = {1, 4}$</td>
<td>0.849</td>
<td>0.833</td>
<td>0.819</td>
<td>0.846</td>
<td>0.897</td>
<td>0.849</td>
</tr>
<tr>
<td>$\mathcal{K} = {1, 4, 7}$</td>
<td>0.810</td>
<td>0.766</td>
<td>0.863</td>
<td>0.736</td>
<td>0.804</td>
<td>0.796</td>
</tr>
<tr>
<td>$\mathcal{K} = {4, 7}$</td>
<td>0.663</td>
<td>0.790</td>
<td>1.167</td>
<td>0.871</td>
<td>1.189</td>
<td>0.936</td>
</tr>
<tr>
<td>$\mathcal{K} = {1, 3} = [8]$</td>
<td>0.773</td>
<td>0.722</td>
<td>0.875</td>
<td>0.822</td>
<td>0.995</td>
<td>0.798</td>
</tr>
</tbody>
</table>
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Conclusions

- Single LTF0 for Brazilian Portuguese recordings
  - Base value of F0 ($F_b$)
    - Lowest EER (16.1 %) considering the eight considered LTF0
    - Used by only 25 % of forensic experts

- Proposed combination of the LTF0 for Brazilian Portuguese recordings
  - $F_b$ (LTF04) combined to the median $\hat{Q}_2$ (LTF02)
    - Lowest EER: 13 %
    - Lowest CLLR: 0.618
    - Scenario: section with 15 second length

- Next steps
  - Other percentiles for $F_b$: derivation considering Gaussian distribution
  - Evaluation for signal-to-noise ratio (SNR) variations and channel mismatch
  - Exploitation of the MVKD function using tensors
Thank you for your attention!

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Proposed combined LTF0 (1)

Step 1 - Divide the $R$ recordings into 2 parts of the same length. First part used as a trace and the second part as a suspect’s model.

Step 2 - Extract the F0 contour of the $R$ traces and of the $R$ suspect’s models in sections of $t_s$ seconds for $s = 1, \ldots, S$.

Step 3 - Compute LTF0$_{k=1,\ldots,8}$ given by $\hat{\mu}$, $\hat{Q}_2$, $\hat{\sigma}$, $\hat{F}_b$, $\hat{\psi}$, $\hat{\eta}$, $\hat{\psi}$ and $\hat{\gamma}$ for all contours extracted in the Step 2.

Step 4 - Computes LR$s$, via MVKD, comparing $R$ traces against all $R$ speaker models for all sections $s$ and for $\hat{F}_b$ combined with other LTF0$_{k=1,\ldots,8}$ $|\text{ LTF0}_k \neq \hat{F}_b$, resulting in matrices of $R \times R$ dimension.

Step 5 - Process the matrices obtained to compute the combined LTF0 EERs.
References


References


Proposed combined LTF0 (4)

Step 1 - Divide the $R$ recordings into 2 parts of the same length. First part used as a trace and the second part as a suspect’s model

Step 2 - Extract the F0 contour of the $R$ traces and of the $R$ suspect’s models in sections of $t_s$ seconds for $s = 1, \ldots, S$

Step 3 - Compute $\text{LTF}0_{k=1,\ldots,8}$ given by $\hat{\mu}, \hat{Q}_2, \hat{\sigma}, \hat{F}_b$, $\hat{\omega}, \hat{\eta}, \hat{\psi}$ and $\hat{\gamma}$ for all contours extracted in the Step 2

Step 4 - Computes LR, via MVKD, comparing $R$ traces against all $R$ speaker models for all sections $s$ and for $\hat{F}_b$ combined with other $\text{LTF}0_{k=1,\ldots,8}$ if $\text{LTF}0_{k} \neq \hat{F}_b$, resulting in matrices of $R \times R$ dimension

Step 5 - Process the matrices obtained to compute the combined LTF0 EERs

Step 6 - Compute Cllr of the LTF0 combinations