Estimating Room Impulse Responses from Recorded Balloon Pop

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Icons of Sound

- Icons of Sound: Architectural Psychoacoustics in Byzantium explores the sensory experience of Hagia Sophia
- Interdisciplinary research with SU Art & Art History, CCRMA; funded via grant from SU Presidential Fund, SiCa
- Virtual acoustic reconstruction; filmic exploration
- Auralization using music created for HS, “Cherubikon”
Hagia Sophia

- Justinian-era religious center
  - Built in 532; mosque in 1453; museum since 1934
- Unprecedented scale and expansive domed design
  - 70m long by 50m high; 11-second reverberation time
  - Grey-veined marble, gold tile, green-blue glass
- Visual, acoustic interplay evokes water imagery
RIR Measurement Approaches

- Loudspeaker/sine sweep, MLS
  - Precise, controlled measurement; logistically difficult
- Impulsive sound source
  - Balloon pop, orchestral whip, starter pistol
  - Balloon pop logistically simple, remotely triggerable, uniform radiation pattern, consistent N-wave waveform
Example Balloon Pop Recording

SU Memorial Church

Mem Chu Response Spectrogram

(original)

(8x)
Balloon Pop Acoustics

- Consistent N-wave waveform; uniform radiation pattern
Auralization with Balloon Pop Recording

- Balloon pop response reveals room acoustic parameters; e.g. reverberation time
- Can sound “comby” when applied to audio
Balloon Pop Spectrogram

\[ n(t) = \begin{cases} \frac{p}{2R} (R - ct), & ct \in [R - \rho, R + \rho] \\ 0, & \text{otherwise,} \end{cases} \]

\[ N(\omega) = \frac{pc}{2R} \frac{\nu \sin(\nu) - \cos(\nu)}{j\nu^2} \]

\[ \nu = \omega c / \rho \]

- N-waves have spectral nulls DC and frequencies proportional to multiples of the inverse balloon diameter
RIR Estimation Approach

- Measure balloon pop response $b(t)$
- Estimate arrival density $e(t)$ along $b(t)$
- Synthesize echo pattern accordingly
- Imprint measured/normalized energy profiles
Normalized Echo Density (NED)

- The NED indicates closeness to Gaussian statistics
- NED is predictive of perceptual differences among echo patterns
To find the recorded balloon pop \( b(t) \) NED, \( b(t) \) is first integrated to convert the N-wave into pulses.
NED, AED Relationship

NED (AED), $\frac{1}{\delta} = 1, 2, 5, 10$ kHz

- NED, AED are related via the echo duration/ bandwidth

\[ \eta(t) = \frac{e(t)}{e(t) + 1/\delta} \]

absolute echo density

normalized echo density

echo duration

normalized echo density -- echoes/second

absolute echo density -- echoes/second
Memorial Church NED

• Given the balloon radius, the full bandwidth NED may be estimated from the recorded balloon pop NED

\[ \eta_h = \frac{\eta_b}{(1 - \eta_b) \cdot 2\rho/\delta c + \eta_b} \]

\[ e(t) = \frac{\eta_b(t) \cdot c/2\rho}{1 - \eta_b(t)} \]
Echo Pattern Synthesis

Synthesized Echo Pattern $p(t)$

- Echo patterns are synthesized (i.i.d. per channel) according to Poisson-distributed arrival times with Gaussian-distributed amplitudes.
- Initial clear arrivals in $b(t)$ may be placed by hand.

\begin{equation*}
\varphi(\tau; t) = \exp\{-\tau/e(t)\}
\end{equation*}

\begin{equation*}
\alpha(t) \sim N(0, 1/e(t))
\end{equation*}
Balloon Pop Response Spatial Character

- The Spatial character of the recorded balloon response is indicated by the inter-channel correlation coefficient.
Measurement Correlation Synthesis

\[ y(t) = M \cdot x(t) \]

\[ M = \begin{bmatrix} \cos \theta & \sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \]

\[ \theta(t) = \frac{\arcsin C(t)}{2} \]

- A stereo pair of echo patterns having a perceived correlation coefficient \( C(t) \) may be generated from a pair of statistically independent sequences.
Band Energy Analysis

- Band energies are found by smoothing squared zero-phase Butterworth filter band outputs
- Estimated band energies are then applied to p(t)
Measured, Extrapolated Band Energies

- Measured band energies may be extrapolated as they approach the noise floor or recording end.
Measured, Extended Balloon Pop Spectrograms

Measured BR Spectrogram

Extended BR Spectrogram
• The measured (upper) and estimated (lower) BR spectrograms are similar
The measured (upper) and estimated (lower) impulse response spectrograms are similar.
Estimated, Measured RIR NED

- The estimated and measured NED profiles indicate a good perceptual match over the duration of the impulse response.
The Hagia Sophia BR contains unwanted noise, starting around 2.7 seconds after the direct path arrival.

The measured T30 is in agreement with published results (C. A. Weitze, J. H. Rindel, C. L. Christensen, A. C. Gade 2009).
Hagia Sophia Estimated Impulse RIR

Hagia Sophia estimated RIR spectrogram

- (balloon response extended wet)
- (balloon response hat wet)
- (impulse response hat wet)
- (impulse response hat)
Summary, Future Work

- Balloon pops provide an inexpensive, convenient way to measure room acoustics
- RIRs estimated from balloon pop recordings seem to match loudspeaker measured RIRs
- Cherubikon auralization; “correction” impulse response development, dodecahedron measured, estimated RIR using a loudspeaker
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