Audio, Video, and their Joint Processing with Applications to Teleconferencing

Cha Zhang and Zhengyou Zhang
Communication and Collaboration Systems Group
Microsoft Research
7/11/2011

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Telepresence

Bell Labs Video Conferencing System (1967)

HP Halo (2005)

Polycom RPX (2006)

Cisco Telepresence (2006)

And Tandberg, Telanetix, Teliris, …

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Telepresence System Objectives

(Wainhouse Research 2007)

- High quality audio and video
- Simplicity
- High reliability
- Environmental excellence

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Telepresence System Objectives

(Wainhouse Research 2007)

- High quality audio and video
  - Audio: Clear, low noise, low latency, echo-free, spatial audio
  - Video: Clear, life size, low noise, low latency, eye contact, 3D
- Simplicity
- High reliability
- Environmental excellence

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Related Systems at MSR

- Interactive whiteboard
- RingCam/RoundTable
- Interactive mobile teleconferencing
- Accelerated instant replay
- Personal telepresence station
- Viewport
- Embedded social proxies

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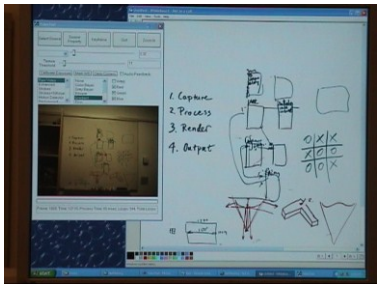
Interactive Whiteboard



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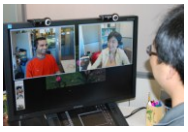
RingCam and RoundTable

Interactive Mobile Teleconferencing

Accelerated Instant Replay

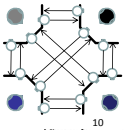
Personal Telepresence Station






Video

Full Mesh Geometry



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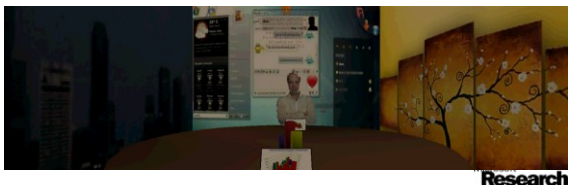
Viewport





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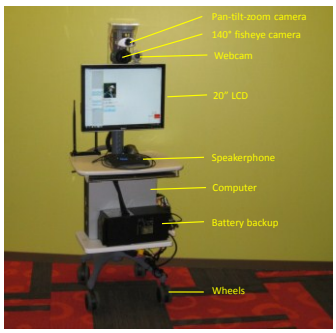
Embodied Social Proxies



Video

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Outline

- Introduction
- Sound source localization with compact mic arrays
- Spatial sound and multi-channel echo cancellation
- Video-based tracking
- Other video processing techniques
- Conclusions and future work

Outline

- Introduction
- Sound source localization with compact mic arrays
  - A maximum likelihood solution
  - Room modeling for enhancing range sensitivity
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• Panoramic view from 5 high-resolution cameras
• Circular 6-microphone array for speech capturing and sound source localization
• Automated speaker switching

SSL Based on Time Difference of Arrival (TDOA)

- Cross-correlation

$$R_{ik}(\tau) = \int x_i(t) x_k(t-\tau) dt,$$

when $\tau = \frac{d}{c}$, one gets the max value. In freq. domain:

$$R_{ik}(\tau) = \int X_i(\omega) X_k^*(\omega) e^{j\omega\tau} d\omega,$$

In case of multiple mics, solve the following using hypothesis testing:

$$\begin{aligned}\mathcal{R}(\mathbf{s}) &= \sum_{i=1}^{P}\sum_{k=1}^{P}\int X_i(\omega)X_k^*(\omega)e^{j\omega(\tau_i-\tau_k)}d\omega, \\ &= \int \Big[\sum_{i=1}^{P} X_i(\omega)e^{j\omega\tau_i}\Big]\Big[\sum_{k=1}^{P} X_k(\omega)e^{j\omega\tau_k}\Big]^* d\omega, \\ &= \int \Big|\sum_{i=1}^{P} X_i(\omega)e^{j\omega\tau_i}\Big|^2 d\omega,\end{aligned}$$

Steered Response Power (SRP)

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SSL Based on TDOA (cont.)

- Generalized cross-correlation

$$\mathcal{R}(\mathbf{s}) = \sum_{i=1}^{P}\sum_{k=1}^{P}\int \Psi_{ik}(\omega) X_i(\omega) X_k^*(\omega) e^{j\omega(\tau_i-\tau_k)} d\omega,$$

  - SRP-PHAT

$$\Psi_{ik}(\omega) = \frac{1}{|X_i(\omega)X_k^*(\omega)|} = \frac{1}{|X_i(\omega)||X_k(\omega)|}$$

$$\mathcal{R}(\mathbf{s}) = \int \Big|\sum_{i=1}^{P} \frac{X_i(\omega)e^{j\omega\tau_i}}{|X_i(\omega)|}\Big|^2 d\omega,$$

  - ML based SRP (weight optimal for 2-mic only)

$$\Psi_{ij}(\omega) = \frac{|X_i(\omega)||X_j(\omega)|}{|N_i(\omega)|^2|X_j(\omega)|^2 + |N_j(\omega)|^2|X_i(\omega)|^2}.$$

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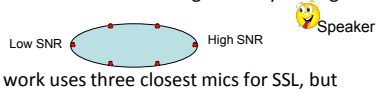
Motivation

- RoundTable uses *directional* microphones
  - All mics point outwards
  - For sound capture, experimental results show:

    Directional mics + mic selection > omni-direcitonal mics + beamforming
  - Signal to noise ratio varies significantly among mics



  - Early work uses three closest mics for SSL, but performance is not great

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Signal Model

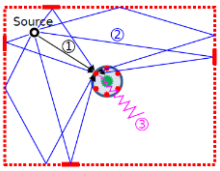
- Model $\mathbf{X}(\omega) = \underbrace{S(\omega)\mathbf{G}(\omega)}_{①} + \underbrace{S(\omega)\mathbf{H}(\omega)}_{②} + \underbrace{\mathbf{N}(\omega)}_{③},$

Received signal: $\mathbf{X}(\omega) = [X_1(\omega), \cdots, X_P(\omega)]^T,$

Direct propagation gain: $\mathbf{G}(\omega) = [\alpha_1(\omega)e^{-j\omega\tau_1}, \cdots, \alpha_P(\omega)e^{-j\omega\tau_P}]^T,$

Environment response: $\mathbf{H}(\omega) = [H_1(\omega), \cdots, H_P(\omega)]^T,$

Additive noise: $\mathbf{N}(\omega) = [N_1(\omega), \cdots, N_P(\omega)]^T.$



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Noise Modeling

- Define:

$$\mathbf{N}^c(\omega) = S(\omega)\mathbf{H}(\omega) + \mathbf{N}(\omega),$$

and assume it follows a zero-mean, independent between frequencies, joint Gaussian distribution

$$p(\mathbf{N}^c(\omega)) = \rho \exp\Big\{-\frac{1}{2}[\mathbf{N}^c(\omega)]^H \mathbf{Q}^{-1}(\omega)\mathbf{N}^c(\omega)\Big\},$$

$$\begin{aligned}\mathbf{Q}(\omega) &= E\{\mathbf{N}^c(\omega)[\mathbf{N}^c(\omega)]^H\} \\ &= E\{\mathbf{N}(\omega)\mathbf{N}^H(\omega)\} + |S(\omega)|^2 E\{\mathbf{H}(\omega)\mathbf{H}^H(\omega)\}\end{aligned}$$

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Estimate Noise Covariance Matrix

$$\begin{aligned}\mathbf{Q}(\omega) &= E\{\mathbf{N}^c(\omega)[\mathbf{N}^c(\omega)]^H\} \\ &= E\{\mathbf{N}(\omega)\mathbf{N}^H(\omega)\} + |S(\omega)|^2 E\{\mathbf{H}(\omega)\mathbf{H}^H(\omega)\}\end{aligned}$$

- First term:

$$E(N_i(\omega)N_j^*(\omega)) = \lim_{K\to\infty}\frac{1}{K}\sum_{k=1}^{K} N_{ik}(\omega)N_{jk}^*(\omega)$$

- Second term (Wang 97, Rui 04):

$$|S(\omega)|^2 E\{\mathbf{H}(\omega)\mathbf{H}^H(\omega)\} \approx \mathrm{diag}(\lambda_1, \cdots, \lambda_P)$$

$$\begin{aligned}\lambda_i &= E\{|H_i(\omega)|^2|S(\omega)|^2\} \\ &\approx \gamma(|X_i(\omega)|^2 - E\{|N_i(\omega)|^2\})\end{aligned}$$

$0 < \gamma < 1$ is an empirical parameter

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Formulation and Solution

- Maximize the likelihood of the received signals

$$p(\mathbf{X}|S,\mathbf{G},\mathbf{Q}) = \prod_{\omega} p(\mathbf{X}(\omega)|S(\omega),\mathbf{G}(\omega),\mathbf{Q}(\omega)),$$

- Results:

$$S(\omega) = \frac{\mathbf{G}^H(\omega)\mathbf{Q}^{-1}(\omega)\mathbf{X}(\omega)}{\mathbf{G}^H(\omega)\mathbf{Q}^{-1}(\omega)\mathbf{G}(\omega)}$$

and the ML based SSL algorithm shall maximize:

$$\int_{\omega} \frac{[\mathbf{G}^H(\omega)\mathbf{Q}^{-1}(\omega)\mathbf{X}(\omega)]^H \mathbf{G}^H(\omega)\mathbf{Q}^{-1}(\omega)\mathbf{X}(\omega)}{\mathbf{G}^H(\omega)\mathbf{Q}^{-1}(\omega)\mathbf{G}(\omega)} d\omega$$

through hypothesis testing.

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Some High-Level Messages

- It's a very general ML framework for multi-microphone SSL
- It does not require known microphone gain pattern (gain is estimated by the algorithm)
- It can weight microphones differently based on their noise variances
- It can handle certain amount of reverberation
- SRP-PHAT is a special case of the framework when SNR is extremely high
- It is equivalent to using a minimum variance distortionless response (MVDR) beamformer for SSL
- For detailed derivations, see Zhang 07.

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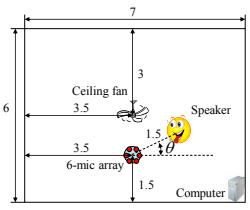
A Synthetic Environment

- An omni-directional mic array in a virtual room
- Two simulated additive noise sources (ceiling fan and computer) at adjustable SNR
- Adjustable reverberation level
- Speaker is placed at different locations (θ=0,36°,72°,...,). Average SSL error rate of all locations is reported.



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Results

Reverberation = 100 ms

Input SNR	SRP-PHAT		Proposed ML SSL	
	< 2°	< 10°	< 2°	< 10°
25 dB	**93.28%**	**94.41%**	92.36%	93.82%
20 dB	**83.35%**	84.92%	83.19%	**84.96%**
15 dB	79.24%	81.15%	**80.30%**	**82.35%**
10 dB	73.87%	76.71%	**76.29%**	**78.75%**
5 dB	66.59%	70.87%	**71.94%**	**75.30%**
0 dB	54.02%	60.78%	**64.19%**	**69.57%**

Reverberation = 500 ms

Input SNR	SRP-PHAT		Proposed ML SSL	
	< 2°	< 10°	< 2°	< 10°
25 dB	**61.53%**	**75.67%**	60.76%	74.57%
20 dB	**60.14%**	**73.88%**	59.79%	73.23%
15 dB	54.76%	**67.14%**	**54.78%**	66.97%
10 dB	52.45%	64.66%	**53.40%**	**65.22%**
5 dB	49.53%	61.96%	**50.80%**	**62.86%**
0 dB	45.11%	57.91%	**47.47%**	**60.14%**

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Real-World Data

- 99 meetings captured in more than 50 rooms with various number of attendees
- 4 minutes each
- Speaker direction manually labeled (6706 frames in total)
- Input SNR ranges from 5 dB to 25 dB
- Report results on the percentage of frames that are within 6° (~20 pixels) and 14° (~40 pixels)

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Results

Conventional Approach (closest 3 mics)		SRP-PHAT (6 mics)		Proposed method (6 mics)	
< 6°	< 14°	< 6°	< 14°	< 6°	< 14°
80.55%	86.85%	81.73%	88.13%	**83.49%**	**90.13%**

15.1% reduction in error

24.9% reduction in error

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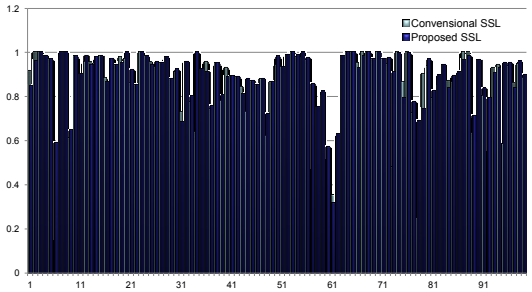
Results (cont.)



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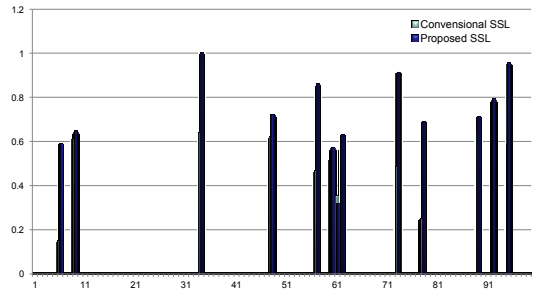
Results (cont.)



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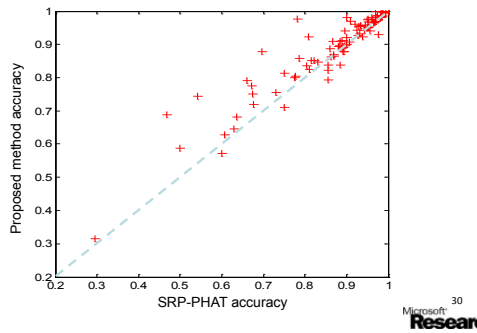
Results (cont.)



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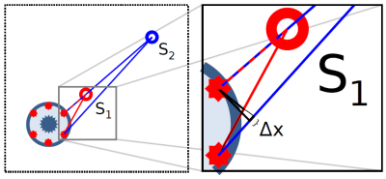
Motivation

- Compact mic array has poor resolution in range and elevation for SSL
- Reverberation degrades SSL performance



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Modeling the Reverberation

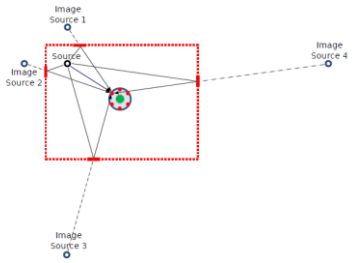
- Energy approximation
  - Wang 97, Rui 04, Zhang 07

$$|S(\omega)|^2 E\{\mathbf{H}(\omega)\mathbf{H}^H(\omega)\} \approx \mathrm{diag}(\lambda_1, \cdots, \lambda_P)$$
$$\lambda_i = E\{|H_i(\omega)|^2|S(\omega)|^2\} \approx \gamma(|X_i(\omega)|^2 - E\{|N_i(\omega)|^2\})$$

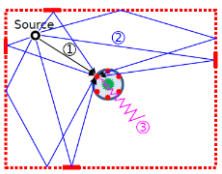
- Measure/estimate full room impulse response (Weinstein 94)
  - Very challenging
  - RIR change rapidly and significantly with the position and orientation of the source

Our Approach: Room Modeling

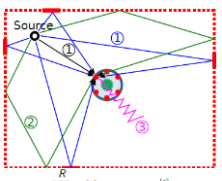
- The image model (Allen 79)



A New Signal Model



$$X_i(\omega) = \underbrace{\alpha_i(\omega)\, e^{-j\omega\tau_i} S(\omega)}_{①} + \underbrace{H_i(\omega)\, S(\omega)}_{②} + \underbrace{N_i(\omega)}_{③}$$



$$X_i(\omega) = \underbrace{\sum_{r=0}^{R} \alpha_i^{(r)}(\omega)\, e^{-j\omega\tau_i^{(r)}} S(\omega)}_{①} + \underbrace{H_i(\omega)\, S(\omega)}_{②} + \underbrace{N_i(\omega)}_{③}$$

Extend the ML Solution

- Consider: $X_i(\omega) = \underbrace{\sum_{r=0}^{R} \alpha_i^{(r)}(\omega)\, e^{-j\omega\tau_i^{(r)}}\, S(\omega)}_{①} + \underbrace{H_i(\omega)\, S(\omega)}_{②} + \underbrace{N_i(\omega)}_{③}$.
- Let: $G_i(\omega) = \sum_{r=0}^{R} \alpha_i^{(r)}(\omega)\, e^{-j\omega\tau_i^{(r)}} = g_i(\omega) e^{-j\varphi_i(\omega)}$

$$g_i(\omega) = \left| \sum_{r=0}^{R} \alpha_i^{(r)}(\omega)\, e^{-j\omega\tau_i^{(r)}} \right| \quad e^{-j\varphi_i(\omega)} = \frac{\sum_{r=0}^{R} \alpha_i^{(r)}(\omega)\, e^{-j\omega\tau_i^{(r)}}}{\left| \sum_{r=0}^{R} \alpha_i^{(r)}(\omega)\, e^{-j\omega\tau_i^{(r)}} \right|}$$

- Approximate: $e^{-j\varphi_i(\omega)} \approx \frac{\sum_{r=0}^{R} \frac{\rho_i^{(r)}}{r_i^{(r)}} e^{-j\omega\tau_i^{(r)}}}{\left| \sum_{r=0}^{R} \frac{\rho_i^{(r)}}{r_i^{(r)}} e^{-j\omega\tau_i^{(r)}} \right|}$ known
- Same solution as before

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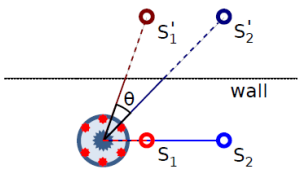
Range Discrimination

- The reflected sound source can help range discrimination
- Reverberation is now our friend!



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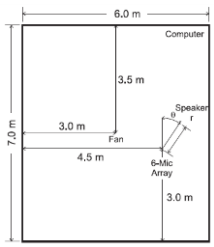
Exp. Results – Synthetic Data

- Synthetic room
- Speaker at 1.3m to the array, tested at 0° elevation, and azimuth $\theta = 0°, 36°, 72°, \ldots$
- Reverberation T_{60} at 250 ms and 500 ms



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Exp. Results – Synthetic Data

Closest Mic. SNR	VAD Voice Frames	ML-SSL $\Delta\theta > 2°$	ML-SSL $\Delta\phi > 1°$	ML-SSL $\Delta r > .15\,m$	R-ML-SSL $\Delta\theta > 2°$	R-ML-SSL $\Delta\phi > 1°$	R-ML-SSL $\Delta r > .15\,m$
25 dB	48	0.4 %	92.0 %	84.6 %	0.4 %	0.2 %	0.2 %
20 dB	47	0.2 %	90.6 %	81.6 %	0.2 %	0.0 %	0.0 %
15 dB	44	1.1 %	88.2 %	80.9 %	1.1 %	0.9 %	0.4 %
10 dB	38	3.4 %	85.6 %	81.6 %	3.4 %	2.9 %	2.1 %
5 dB	29	15.0 %	86.0 %	90.1 %	15.0 %	14.3 %	6.9 %
0 dB	16	24.8 %	85.1 %	94.3 %	24.8 %	22.2 %	15.5 %

Table I
ERROR RATES FOR SYNTHETIC DATA, $T_{60} = 250\,ms$.

Closest Mic. SNR	VAD Voice Frames	ML-SSL $\Delta\theta > 2°$	ML-SSL $\Delta\phi > 1°$	ML-SSL $\Delta r > .15\,m$	R-ML-SSL $\Delta\theta > 2°$	R-ML-SSL $\Delta\phi > 1°$	R-ML-SSL $\Delta r > .15\,m$
25 dB	47	1.3 %	94.3 %	87.5 %	1.3 %	1.9 %	1.2 %
20 dB	45	1.1 %	93.2 %	86.3 %	1.1 %	1.7 %	1.5 %
15 dB	41	1.4 %	93.8 %	86.8 %	1.4 %	1.1 %	0.9 %
10 dB	38	2.6 %	94.1 %	88.5 %	2.6 %	2.6 %	1.6 %
5 dB	33	6.5 %	92.3 %	89.0 %	6.5 %	5.4 %	2.2 %
0 dB	23	21.4 %	91.0 %	93.0 %	21.4 %	19.3 %	12.4 %

Table II
ERROR RATES FOR SYNTHETIC DATA, $T_{60} = 500\,ms$.

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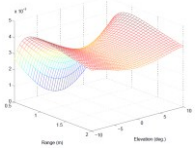
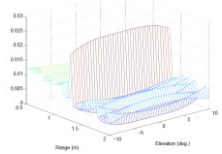
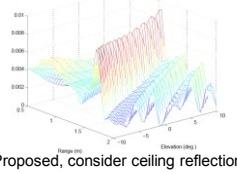
Exp. Results – Synthetic Data



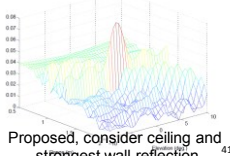
ML-SSL



Proposed, consider strongest wall reflection



Proposed, consider ceiling reflection



Proposed, consider ceiling and strongest wall reflection

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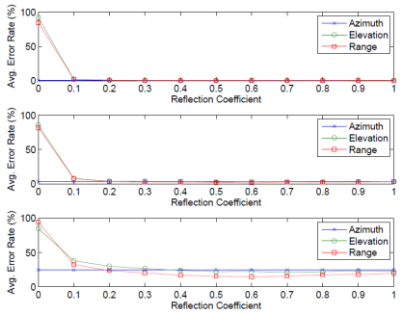
Sensitivity to Wall Reflection Coef.



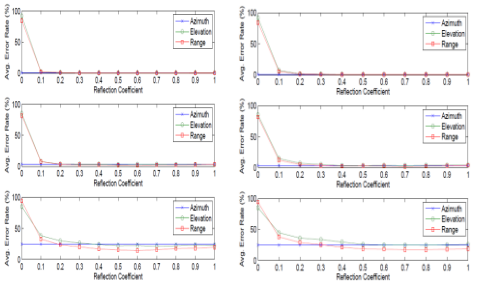
25 dB SNR

10 dB SNR

0 dB SNR

Microsoft Research

Sensitivity to Number of Walls

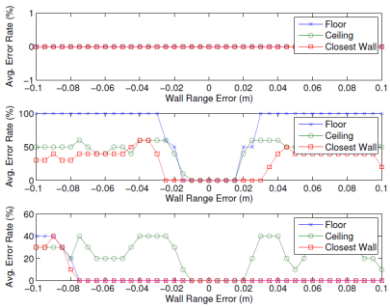


All walls considered

Only considers floor, ceiling and closest wall

Microsoft Research

Sensitivity to Wall Distance Error



Azimuth errors

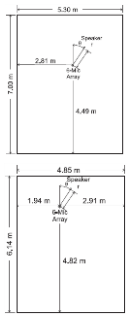
Elevation errors

Range errors

Microsoft Research

Exp. Results – Real Room Data

- Room 1
  - Distance to wall estimated using RoundTable device
  - 3 Closest reflectors used
- Room 2
  - Distance to wall measured by an ultrasonic range finder (1cm res.)
  - Reflection coef. set to 0.3



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Exp. Results – Real Room Data

Speaker Position	# of Frames	ML-SSL			R-ML-SSL		
		$\Delta\theta > 10°$	$\Delta\phi > 5°$	$\Delta r > 0.15$	$\Delta\theta > 10°$	$\Delta\phi > 5°$	$\Delta r > 0.15$
$\theta \approx 0°, \phi \approx 2.5°, r \approx 1.70\,m$	11	0%	0%	55%	0%	0%	0%
$\theta \approx 60°, \phi \approx 2.5°, r \approx 1.47\,m$	21	0%	5%	95%	0%	9%	9%
$\theta \approx 120°, \phi \approx 2.5°, r \approx 1.37\,m$	9	0%	0%	33%	0%	11%	11%

Room 1

Speaker Position	# of Frames	ML-SSL			R-ML-SSL		
		$\Delta\theta > 10°$	$\Delta\phi > 5°$	$\Delta r > 0.15$	$\Delta\theta > 10°$	$\Delta\phi > 5°$	$\Delta r > 0.15$
$\theta \approx 60°, \phi \approx 26°, r \approx 1.85\,m$	77	0%	0%	100%	0%	5%	1%
$\theta \approx 60°, \phi \approx 18°, r \approx 2.40\,m$	71	0%	0%	87%	0%	3%	16%
$\theta \approx 120°, \phi \approx 32°, r \approx 1.60\,m$	72	3%	3%	96%	3%	3%	3%
$\theta \approx 120°, \phi \approx 22°, r \approx 2.15\,m$	68	0%	3%	90%	0%	2%	3%
$\theta \approx 180°, \phi \approx 15°, r \approx 3.10\,m$	82	1%	10%	99%	1%	2%	27%
$\theta \approx 180°, \phi \approx 12°, r \approx 4.00\,m$	76	0%	24%	96%	0%	1%	17%
$\theta \approx 240°, \phi \approx 36°, r \approx 1.45\,m$	75	12%	12%	96%	12%	9%	13%
$\theta \approx 300°, \phi \approx 40°, r \approx 1.40\,m$	84	7%	7%	98%	7%	6%	34%

Room 2

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How to Estimate Room Model

- Visual methods
  - Range sensors
  - Landmark based (Kimber 09)
- Acoustic methods
  - Acoustic imaging (Moebus 07, O'Donovan 08)
  - Image model (Allen 79)
    - Single mic (Aprea 09, Antonacci 10, Dokmanic 11)
    - Mic arrays (Filos 10, Canclini 11)

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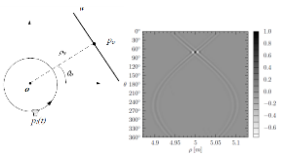
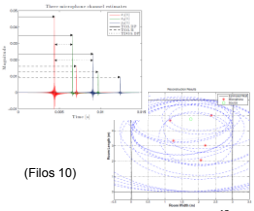
Image Model based Methods

- Two steps:
  - Measure room impulse responses (RIRs)
  - Infer room model



(Aprea 09)



(Filos 10)

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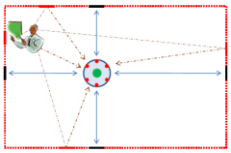
Representation



$$R = \{(a_i, d_i, \theta_i, \phi_i)\}_{i=1}^{6}$$

Reflection coef. of wall i.

3D position of wall i w.r.t. array center

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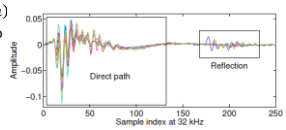
RIR Modeling

- Signal observed at mic m:
  - $y_m(n) = h_m(n) * s(n) + u_m(n)$
  - $h_m(n)$: RIR from array center to mic m
- Only consider early reflections



$h_m^{(dp)}(n)$: direct path IR from array center to mic m

$h_m^{(r_i,\theta_i,\phi_i)}(n)$: IR at mic m from perfect wall at (r_i, θ_i, ϕ_i) (WIR)

R : number of modeled walls

Then

$$h_m(n) \approx h_m^{(dp)}(n) + \sum_{i=1}^{R} \rho^{(i)} h_m^{(r_i,\theta_i,\phi_i)}(n) + v_m(n)$$

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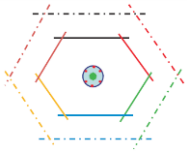
Infer the Wall Locations

- In vector form:

$$\mathbf{h} \approx \mathbf{h}^{(dp)}(n) + \sum_{i=1}^{R} \rho^{(i)} \mathbf{h}^{(r_i,\theta_i,\phi_i)} + \mathbf{v}$$

- Solve:

$$\min_{\mathbf{a}} \|\mathbf{h}_{room} - \mathbf{H}\mathbf{a}\|_2^2 + \lambda \|\mathbf{a}\|_1$$



- Note we obtain a sparse solution for $\boldsymbol{a}$ due to L_1 optimization.
- Solved using LASSO (Tibshirani 96).

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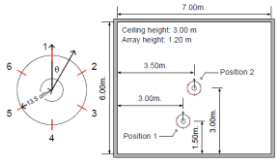
Exp. Results – Synthetic Data

- 6x7x3m room, 300ms reverberation
- Reflection coef. of 0.77
- SNR ~20dB
- Position 2 is more challenging



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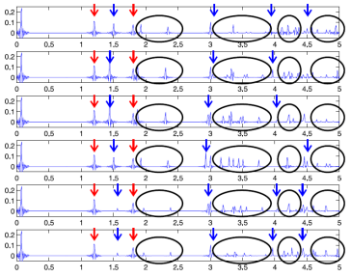
Exp. Results – Synthetic Data



Blue arrows: 1st order reflections with walls
Red arrows: 1st order reflections with floor/ceiling
Ellipses: high order reflections

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Exp. Results – Synthetic Data

Ground Truth			Estimates		
r (m)	θ (°)	ϕ (°)	r (m)	θ (°)	ϕ (°)
1.200	0	-90	1.200	0	90
1.800	0	90	1.800	0	90
4.500	0	0	4.502	0	0
4.000	90	0	4.000	90	0
1.500	180	0	1.500	180	0
3.000	270	0	3.005	270	0

Position 1

Ground Truth			Estimates		
r (m)	θ (°)	ϕ (°)	r (m)	θ (°)	ϕ (°)
1.200	0.0	-90	1.200	0.0	90
1.800	0.0	90	1.800	0.0	90
3.000	0.0	0	3.001	0.0	0
3.500	90.0	0	3.501	90.0	0
3.000	180.0	0	3.001	180.0	0
3.500	270.0	0	3.501	270.0	0

Position 2

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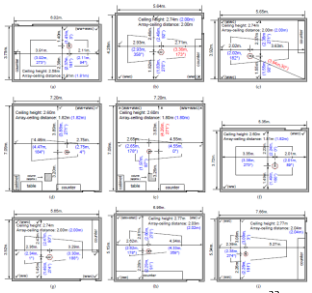
Exp. Results – Real Room Data

- 9 conference rooms
- RoundTable device
  - WIR measured in anechoic chamber
  - Device on the table, no floor



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Exp. Results – Real Room Data

Room	Ground Truth			Estimates			
	r (m)	θ (°)	ϕ (°)	r (m)	θ (°)	ϕ (°)	Refs
A	1.81	0	90	1.81	0	90	–
	1.40	0	0	1.41	3	0	111
	2.11	90	0	2.11	94	0	111
	2.36	180	0	2.37	181	0	100
	3.91	270	0	3.92	273	0	100
B	2.00	0	90	2.00	0	90	–
	2.93	0	0	2.93	358	0	101
	2.46	90	0	2.46	92	0	100
	2.71	180	0	3.36	173	0	001
	1.82	270	0	1.83	270	0	101
C	2.00	0	90	2.00	0	90	–
	3.63	0	0	–	–	–	–
	–	–	–	3.94	30	0	100
	1.55	90	0	1.55	90	0	101
	2.02	180	0	2.02	182	0	102
	2.37	270	0	2.38	271	0	101
D	1.82	0	90	1.82	0	90	–
	2.75	0	0	2.75	4	0	011
	3.20	90	0	–	–	–	–
	4.46	180	0	4.47	184	0	100
	3.89	270	0	3.88	271	0	101
E	1.80	0	90	1.80	0	90	–
	4.55	0	0	4.55	0	0	111
	3.26	90	0	–	–	–	–
	2.65	180	0	2.65	178	0	111
	3.83	270	0	4.26	271	0	022
F	1.81	0	90	1.82	0	90	–
	2.23	0	0	2.24	0	0	101
	2.01	90	0	2.01	89	0	001
	1.49	180	0	1.49	180	0	110
	3.35	270	0	3.36	273	0	010
G	2.00	0	90	2.00	0	90	–
	2.36	0	0	2.34	1	0	111
	2.47	90	0	2.47	90	0	101
	3.29	180	0	3.30	188	0	101
	1.45	270	0	1.46	274	0	111
H	2.03	0	90	2.02	0	90	–
	4.34	0	0	4.33	359	0	010
	2.28	90	0	2.29	91	0	110
	2.26	180	0	2.62	178	0	121
	2.87	270	0	2.86	270	0	121
I	2.04	0	90	2.04	0	90	–
	3.08	0	0	3.09	3	0	101
	5.27	90	0	–	–	–	–
	2.26	180	0	2.26	181	0	101
	2.39	270	0	2.38	274	0	102

Most walls are identified correctly, with a typical resolution of 1 cm.
Some distant walls are not correctly detected, though they won't impact SSL performance.

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Outline

- Introduction
- Sound source localization with compact mic arrays
  - A maximum likelihood solution
  - Room modeling for enhancing range sensitivity
  - Joint audio/visual speaker localization
- Spatial sound and multi-channel echo cancellation
- Video-based tracking
- Other video processing techniques
- Conclusions and future work

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Motivation

- SSL only is still not accurate enough
  - Reverberation
  - Noise
- Can we use the panoramic video for help?

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Previous Work

- SSL only speaker pointing (Polycom iPower 900)
  - Sensitive to reflections and noises
- SSL + face detection decision level fusion (DLF)
  - Very popular (Kapralos 02, Yoshimi 02)
  - RingCam used this approach (Cutler 02)

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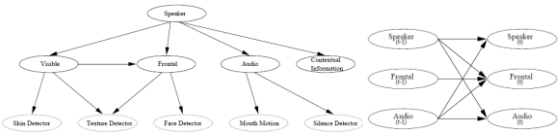
Previous Work

- Graphic models for audio/visual fusion (Pavlović 01, Beal 02)
  - Intuitive way to fuse multimodal data
  - Inference could be time-consuming



(Pavlović 01)

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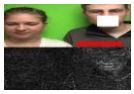
Previous Work

- Audio visual synchrony (Cutler00, Hershey00, Nock03)
  - Use mutual information between AV signals
  - Search for high correlation between AV



Light pixel represents high mutual information between AV (Nock03)

- Speaker tracking (Vermaak 01, Chen 04)
  - Fuse audio/video information using particle filters
  - Still need detection first

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Why Is The Problem Hard?

- People don't always look at the camera
- There can be many meeting attendees
- Color calibration is hard, hence skin color-based face detection doesn't work
- Extremely low computation budget (100 MIPS)
- Image resolution is low, face can be as small as 10x10 pixel

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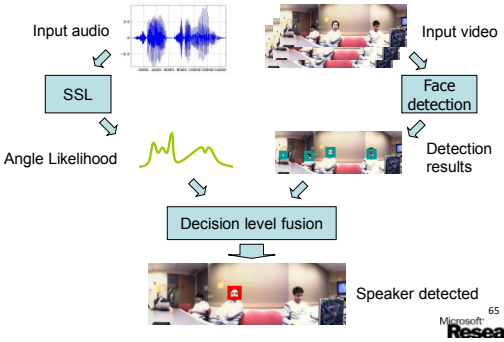
Decision Level Fusion



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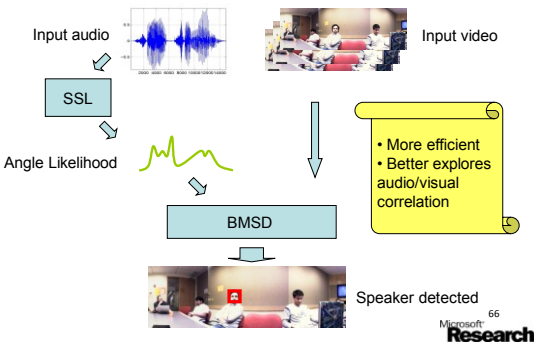
BMSD



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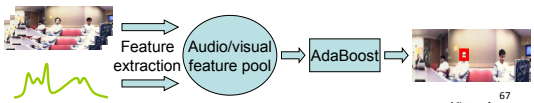
AdaBoost

- Adaptively focus on the difficult examples
- Boost the weak learner to a strong classifier by linear combination

$$H(x) = \Sigma \alpha_t * h_t(x)$$

- Greedily pick the best feature according to the current sample weight distribution
- Can be used for automatic feature selection



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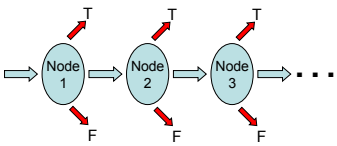
Attention Cascade



- Each node can contain one or multiple features
- Most negative examples are rejected at early stages
- Extremely efficient

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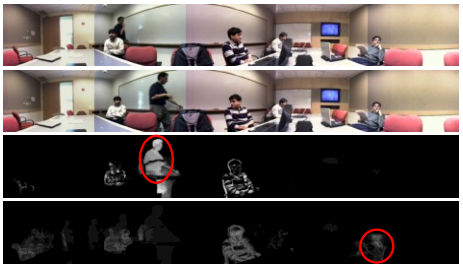
Video Feature Extraction



$$M_t = min\left(|I_t - I_{t-1}|, |I_t - I_{t-2}|\right)$$
$$R_t = \alpha M_t + (1-\alpha) R_{t-1}$$

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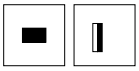
Video Feature Extraction (cont.)



Haar features (Viola 01)
on all three images.

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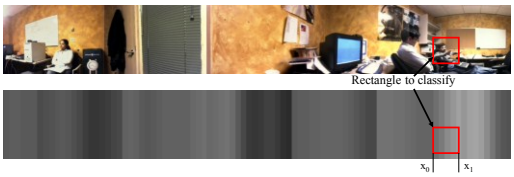
Audio Feature Extraction



1. $\frac{L^l_{\max}-L^g_{\min}}{L^g_{\max}-L^g_{\min}}$	2. $\frac{L^l_{\min}-L^g_{\min}}{L^g_{\max}-L^g_{\min}}$	3. $\frac{L^l_{avg}-L^g_{\min}}{L^g_{\max}-L^g_{\min}}$
4. $\frac{L^l_{\text{mid}}-L^g_{\min}}{L^g_{\max}-L^g_{\min}}$	5. $\frac{L^l_{\max}}{L^l_{\min}}$	6. $\frac{L^l_{\max}}{L^l_{avg}}$
7. $\frac{L^l_{\min}}{L^l_{avg}}$	8. $\frac{L^l_{\text{mid}}}{L^l_{avg}}$	9. $\frac{L^l_{\max}-L^l_{\min}}{L^l_{avg}}$
10. $\frac{L^l_{\max}}{L^g_{\max}}$	11. $\frac{L^l_{\min}}{L^g_{\max}}$	12. $\frac{L^l_{avg}}{L^g_{\max}}$
13. $\frac{L^l_{\text{mid}}}{L^g_{\max}}$	14. $\frac{L^l_{\max}-L^l_{\min}}{L^g_{\max}}$	15. $L^g_{\max}-L^l_{\max}<\epsilon$

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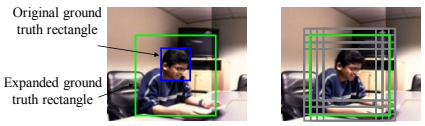
Training and Testing



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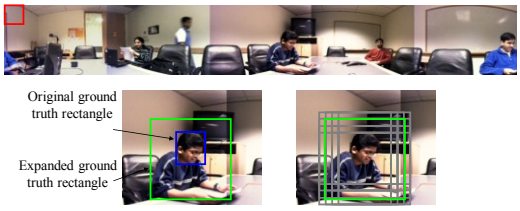
Training and Testing



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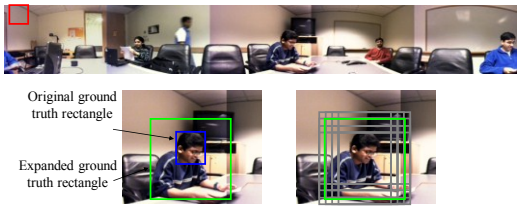
Training and Testing



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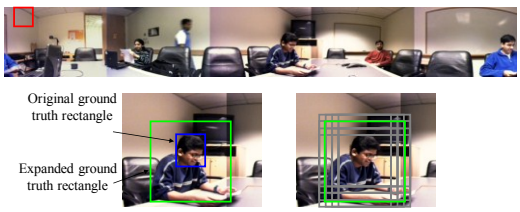
Training and Testing



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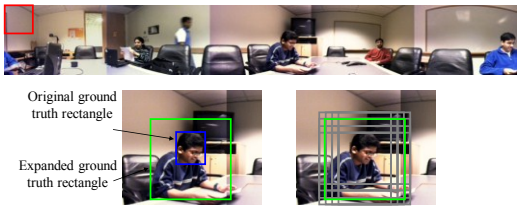
Training and Testing



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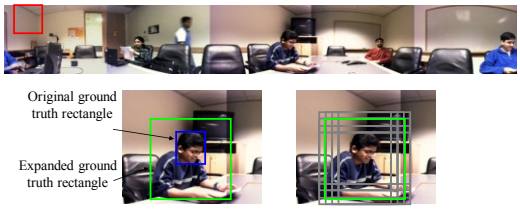
Training and Testing



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Merge of Detected Windows

- Multiple detections could exist for a frame
- Output a single speaker location
- Two methods to merge the windows
  - Projection and merge (PAM)
    - Project to azimuth axis, accumulate histogram
    - Find peak of histogram
    - Average nearby windows
  - Top N merge (TNM)
    - Select top N windows with highest confidence
    - Apply PAM above

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Experiments

- Training: 93 meetings, 3204 labeled frames in 10 different conference rooms
- Testing: 82 meetings, 1502 labeled frames in 10 meeting rooms (different from training)
- Speaker detection in each frame independently
- Compare SSL-only, DLF (SSL+MPD) and BMSD

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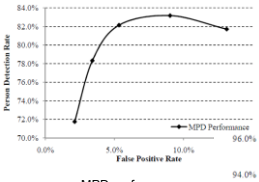
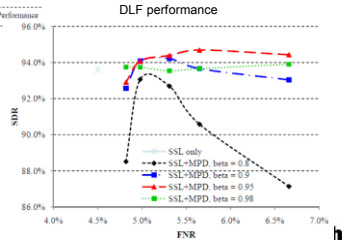
Decision Level Fusion

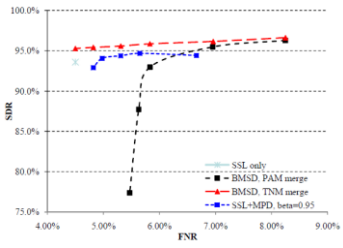


MPD performance

DLF performance



Speaker Detection Performance



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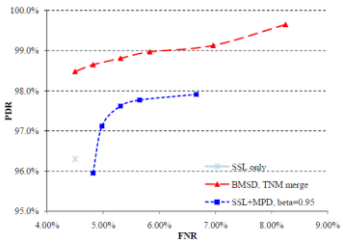
Person Detection Performance



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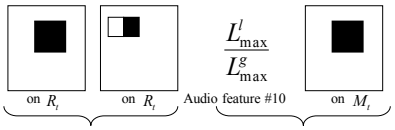
Features Selected by AdaBoost



- BMSD much faster than DLF
  - Audio features help pruning
  - Audio features are extremely fast to compute

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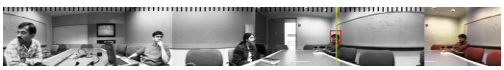
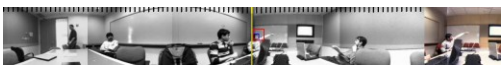
Examples





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Outline

- Introduction
- Sound source localization with compact mic arrays
- Spatial sound and multi-channel echo cancellation
  - Head phone based spatial sound
  - Loudspeaker spatial sound
  - Multi-channel echo cancellation
- Video-based tracking
- Other video processing techniques
- Conclusions and future work

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Motivation

- Current audio conferencing systems
  - Monaural → adequate for 1-to-1
  - Poor when #people > 2
- Why poor?
  - All the voice streams are intermixed into a single one
  - Huge cognitive load: *Do 2 things simultaneously*
    - *Associate voice signals to the speaker*
    - *Comprehend what is being discussed*

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Benefits of Spatial Audio

- Human's cocktail party effect
  - Selective attention
  - Only spend effort on comprehension
- Brain rejects incoherent signals at two ears
  - Reverberation & noise are disregarded (not for mono!)
- Benefits (Baldis 01)
  - Memory
  - Focal Assurance
  - Perceived Comprehension
  - Listener's Preference

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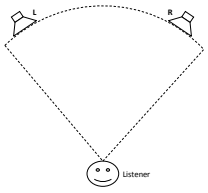
Multiparty Spatial Audio Conferencing

- Virtual seating



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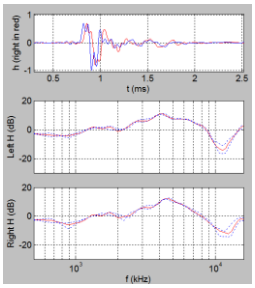
Headphone based Spatial Sound

- Situations requiring privacy
  - Open offices, public spaces, home office, etc
  - On-the-go: mobile devices
- Modern hardware
  - high-quality stereo ear-canal headphones
  - Compact Bluetooth headsets (monaural)
- Controlled environment than loudspeakers
- Easy job for AEC!

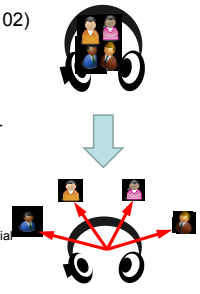
Background

- HRTF/HRIR (Algazi 01)
  - Linear response of each ear to
    - Each azimuth & elevation
    - Captured in an anechoic room
  - Contributing factors
    - Head shadow
    - Pinna/concha/torso
    - Air absorption
  - Gives sense of directivity
    - Individualization is hard



Background

- Headphone "virtualization" (Zlzer 02)
  - Input: regular audio samples
  - Output: simulating a listening environment
    - Localization & externalization
- Model the signal path (Schroeder 62, Stautner 82)
  - transmitter, medium & listener
  - Room response
    - Most important factor for externalization
    - Classical solution: various forms of artificial "reverb"
      - e.g. Schroeder's original comb filters



Challenges & Solution

- Unique requirements for conferencing
  - True room response is subtle
  - HRTF calibration is difficult
  - Sensitivity to human voice
- Higher realism is the solution
  - Capture “combined” transfer function
  - One or few models suffices
  - Localized parameterization possible
  - More computation but acceptable today

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Offline Measurement

- Overall transfer function

$$Y(\omega) = H_l H_r H_t X(\omega) + N$$

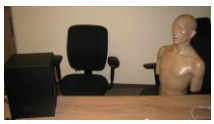
- Probe signal
  - Exponential chirp

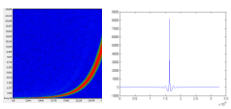
$$x(t) = \sin k_t e^{k_2 t}$$

  - de-convolution
    - At high SNR:

$$\hat{h} = y * x(-t) \approx h * x(t) * x(-t) \approx h$$

  - TBD
    - Comparison & Noise analysis





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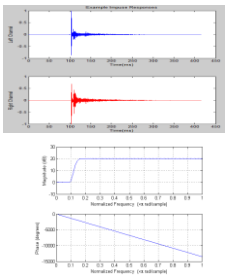
Post-processing

- Sounds bad if use as is
- Alignment & truncation
- Equalization
  - Match the spectrum of the original and processed signal
- Acoustic ratio
  - Between the direct component & the rest
  - Parameterization & personalization



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Online Synthesis

- Partitioning the filters in time
  - Short filter h^s
    - Location dependent, up to 10ms
    - Source, HRTF & early reflections
  - Long filter h^l
    - Location independent, up to 100+ ms
    - Reverberation: omni-directional
- Lower complexity implementation

$$y_i(t;i) = x_i(t) * h_i^s(t;i) + h^l(t) * \sum_j x_j(t)$$

$$y_l(t) = \sum_i y_l(t;i)$$

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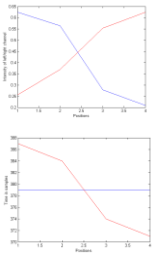
Animation

- Important for added realism
  - Natural head motion while talking
  - With video, help resolve HRTF mismatch
- Classical limitation of non-model based approach
  - Non-parameterized $h_i^s(t;i) \rightarrow h_i^s(t;\phi)$
  - Too many to measure
- Efficient implementation
  - Extract and interpolate three cues: AR, IID, ITD
  - Locally modify transfer function
    $h_i^s(t;\phi) = \Delta\alpha h_i^s(t - \Delta\theta; i)$
  - TBD: smooth, large range animation



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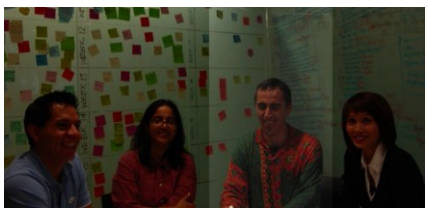
Demo

- Please put on headphone



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Motivation

- People do not like to wear headphones in a remote meeting
- Need a loud speaker solution
  - Challenges
    - User's head moves around
    - Requires multi-channel echo cancellation

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Amplitude Panning

- Well known method (Pullki 97)
- Delay and Gain Modulation
  - Delay

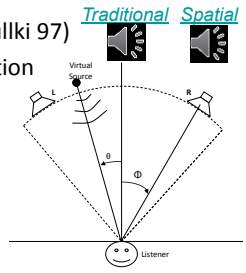
    $\Delta_R = D - D\cos(\lambda(\Phi - \Theta))$

    $\Delta_L = D - D\cos(\lambda(\Phi + \Theta))$

    $D=0.45ms \quad 1 \le \lambda \le \pi/(2\Phi)$
  - Gain

    $G_R = \cos(\lambda(\Phi - \Theta)/2)$

    $G_L = \cos(\lambda(\Phi + \Theta)/2)$



- Only create spatial sound between the loudspeakers

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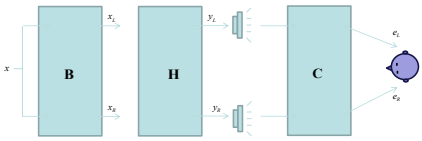
HRTF Based Schemes

- HRTF based method through crosstalk cancellation
  - Binaural sound reproduction over **loudspeaker** with crosstalk canceller



- Organization
  - B : Binaural synthesis
  - H : crosstalk canceller : inversion of C
  - C : transmission path or acoustic channel

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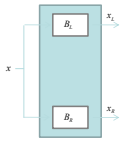
Binaural Synthesis

- Locating sound images around the listener by filtering the monaural input signal with the HRTF for a given angle of incidence.



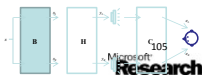
$$\mathbf{x} = \begin{bmatrix} x_L \\ x_R \end{bmatrix} = \begin{bmatrix} B_L \\ B_R \end{bmatrix} x = \mathbf{B}x$$

x : input monaural signal

x_L and x_R : binaural signals for left and right

B_L and B_R : HRTF for left and right ear

- Convolution with pre-measured HRTF



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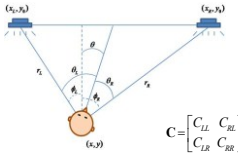
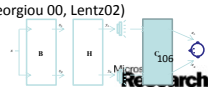
The Dynamic Acoustic Channel



$$\begin{cases} \theta & \text{: head rotation} \\ \theta_L, \theta_R & \text{: azimuths to loudspeakers} \\ (x, y) & \text{: head position} \end{cases}$$

$$\mathbf{C} = \begin{bmatrix} C_{LL} & C_{RL} \\ C_{LR} & C_{RR} \end{bmatrix} \Rightarrow \mathbf{C}_d = \begin{bmatrix} \frac{1}{r_L} z^{-d_L} C_{LL} & \frac{1}{r_R} z^{-d_R} C_{RL} \\ \frac{1}{r_L} z^{-d_L} C_{LR} & \frac{1}{r_R} z^{-d_R} C_{RR} \end{bmatrix}$$

- Adjusting azimuth for HRTFs according to tracking information (Gardner 97)
- Involving time delay and level attenuation
- Tracking using electromagnetic trackers (Georgiou 00, Lentz02)
- Tracking using webcams (Kyriakakis 98, López 99, Lentz 06, Kim 08)



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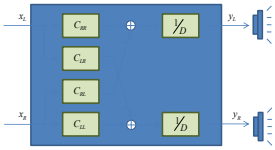
Dynamic Crosstalk Cancellation

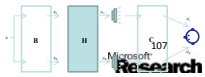
- Inverse the acoustic transfer matrix **C**



$$\mathbf{H} = \mathbf{C}^{-1} = \begin{bmatrix} C_{LL} & C_{RL} \\ C_{LR} & C_{RR} \end{bmatrix}^{-1} = \begin{bmatrix} C_{RR} & -C_{RL} \\ -C_{LR} & C_{LL} \end{bmatrix} \frac{1}{D},$$

$$D = C_{LL} C_{RR} - C_{LR} C_{RL}.$$

- Direct inverse is unstable
  - **H** is adaptively obtained by least mean square (LMS) method



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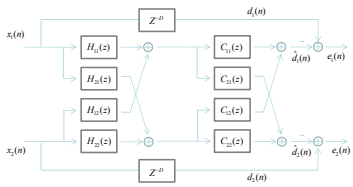
Crosstalk Cancellation with LMS



$$\begin{cases} C_{ml}(z) & \text{: Acoustic channels} \\ H_{nk}(z) & \text{: CTX filters} \end{cases}$$

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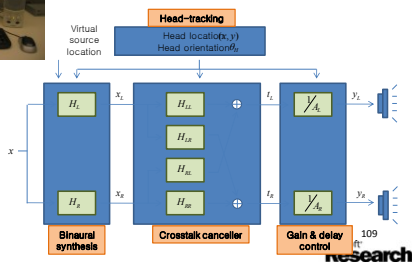
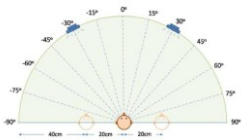
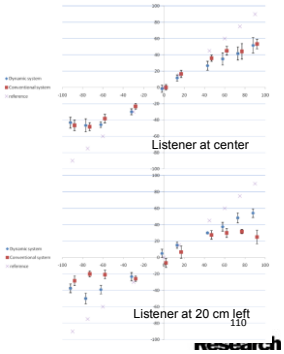
Our Complete System



Listening Test

- Pink noise sound source
- Subjects asked to identify virtual sound direction, which is compared with the ground truth

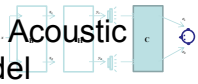




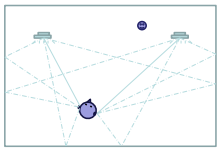
Adding a Room Model

- Crosstalk canceller suffers from room reverberation. HRTFs only represent the *direct path* of acoustic channel.
- Room model?
  - Simplified room model often sufficient (e.g., SSL)
  - Acoustic measurement possible;

Room Model Based Acoustic Channel Model



- New acoustic channel model
  - Summation of the responses for the individual rays from 6 walls as well as direct path from real loudspeaker.



$$C_{nm} = \sum_{k=0}^{N_r} \frac{\beta_k}{r_{mk}} z^{-\Delta_{mk}} C_{nm}(\angle_k)$$

β_k : reflection coeff. for k-th image of m-speaker
r_k : distance from k-th image of m-speaker
$-\Delta_k$: delay from k-th image of m-speaker
$C_{nm}(\angle_k)$: HRTF from k-th image of m-speaker to n-ear

$$\mathbf{C} = \begin{bmatrix} C_{LL} & C_{RL} \\ C_{LR} & C_{RR} \end{bmatrix} \Rightarrow \mathbf{C} = \begin{bmatrix} \sum_{k=0}^{N_r} \frac{1}{r_{LL}} z^{-\Delta_{LL}} C_{LL}(\angle_k) & \sum_{k=0}^{N_r} \frac{1}{r_{RL}} z^{-\Delta_{RL}} C_{RL}(\angle_k) \\ \sum_{k=0}^{N_r} \frac{1}{r_{LR}} z^{-\Delta_{LR}} C_{LR}(\angle_k) & \sum_{k=0}^{N_r} \frac{1}{r_{RR}} z^{-\Delta_{RR}} C_{RR}(\angle_k) \end{bmatrix}$$

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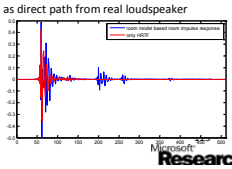
Room Model Based Crosstalk Canceller

- Procedure
  - Room model estimation
    - Obtaining reflection coefficients and configuration of walls
  - Calculating each ray individually
    - Taking account of attenuation by reflection and distance of the path
  - Determining HRTFs
    - Corresponding to direction of the incoming ray.
  - Summation of the responses
    - For the individual rays from 6 walls as well as direct path from real loudspeaker
- Example of transmission channel based on room model
  - C_{RR}
  - Including first reflections from 6 walls



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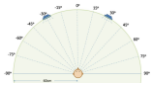
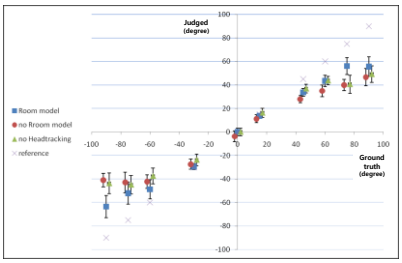
User Study



- Listener at center in reverberant room



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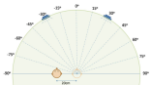
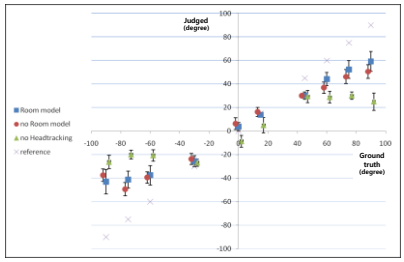
User Study



- Listener at 20cm left in reverberant room



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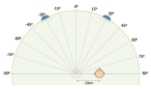
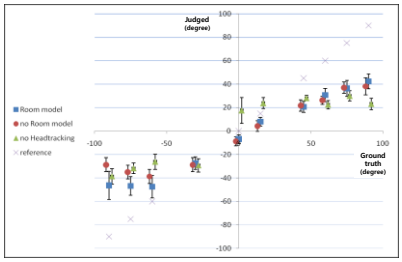
User Study



- Listener at 20cm right in reverberant room



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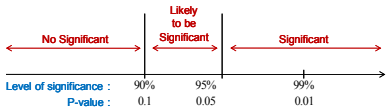
User Study

- Student t-test
  - Assessing whether the means of two groups are statistically different from each other
  - Comparing absolute value of difference between ground-truth and judged azimuth
    - $|reference_i - Judged_{i,n}|$, where i and n are azimuth index and subject index



- T-test Results
  - Room-model vs. no Room-model $p = 0.0007893 < 0.05$
    - ➔ There is significant difference between the two method
  - Head-tracking vs. no Head-tracking $p = 0.0000000483052 < 0.05$
    - ➔ There is significant difference between the two method.

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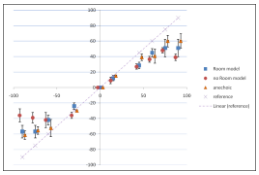
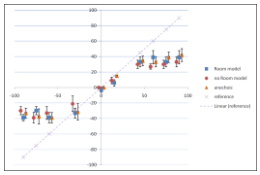
User Study

- Results comparison between 5 good listeners and 5 bad listeners (user at center, no head tracking)

Best 5



worst 5



Differences for virtual sources located outside of loudspeaker
Differences for 3 types
Best 5 : Anechoic > Room model > no Room model
Worst 5 : Anechoic = Room model = no Room model

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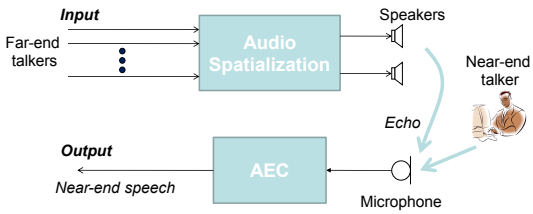
Outline

- Introduction
- Sound source localization with compact mic arrays
- Spatial sound and multi-channel echo cancellation
  - Head phone based spatial sound
  - Loudspeaker spatial sound
  - Multi-channel echo cancellation
- Video-based tracking
- Other video processing techniques
- Conclusions and future work

Challenges and Previous Work

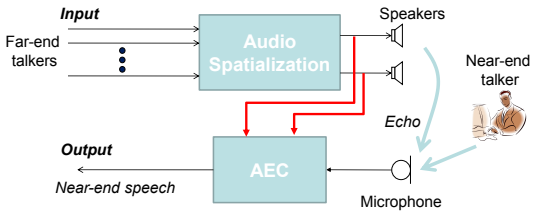
- Stereo ACE suffers from the mis-convergence problem (Sonfhi 95)
- In order to de-correlate the speaker signals
  - Adding nonlinearity (Benesty 98)
  - Adding noise (Sonfhi95, Gilloire 98)
- Adaptive filtering
  - NLMS (Yensen 01)
  - Kalman filtering (Enzner 06)
  - Constrained Kalman filtering (Zhang 08)

Multichannel AEC



- **Question:** *Which reference signals to use?*

Approach 1: Use Speaker Signals



- **Our solution:** Kalman Filtering (general RLS)
- Possible problem: Correlation between speaker signals

Problem Statement: Speaker based

- Speaker Signals:
- Speaker's room response: *L*-tap filter
- Microphone input: Echo

where

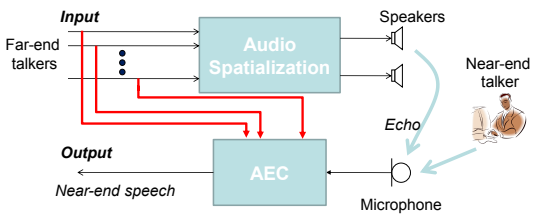
Multichannel AEC: Speaker-based

- Kalman Filter (Generalized RLS)

where is the aging factor and changes over time

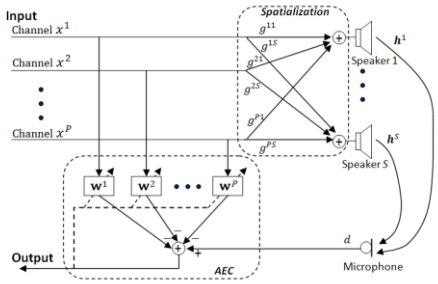
- When , Kalman Filter ⇨ Traditional RLS
- *We model ambient noise.*

Approach 2: Use Far-End Channels



- Cancel each individual far-end speech
- **Our solution:** Constrained Kalman filtering

Multichannel AEC: CKF Diagram



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Problem Statement

- Remote channels: $\{X^i \mid i = 1, \ldots, P\}$
- Spatialization on S speakers: $Y^s = \sum_{i=1}^{P} G^{is} X^i$
- Speaker's room response: L-tap filter

$$\boldsymbol{H}_t^s = [H_t^s, H_{t-1}^s, \ldots, H_{t-L-1}^s]^T$$

- Microphone input: Echo

$$D_t = \sum_{i=1}^{P} \sum_{s=1}^{S} G^{is} \left(H_t^s X_t^i + H_{t-1}^s X_{t-1}^i + \cdots + H_{t-L-1}^s X_{t-L-1}^i \right) = \sum_{i=1}^{P} \sum_{s=1}^{S} G^{is} \boldsymbol{H}_t^{s\,T} \boldsymbol{X}_t^i$$

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Problem Statement (cont'd)

- Determine the echo cancellers:
  - one per remote channel i: L-tap filter

$$\boldsymbol{W}_t^i = [W_t^i, W_{t-1}^i, \ldots, W_{t-L-1}^i]^T$$

such that echo is cancelled, i.e.,

$$D_t - \sum_{i=1}^{P} \boldsymbol{W}_t^{i\,T} \boldsymbol{X}_t^i = 0$$

- Constraint: **W_t^is are not mutually independent**

$$D_t = \sum_{i=1}^{P} \sum_{s=1}^{S} G^{is} \boldsymbol{H}_t^{s\,T} \boldsymbol{X}_t^i \quad \Rightarrow$$

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Constrained Kalman Filtering

- State Vector: Echo cancellers + Speaker RIR filters
  $$\boldsymbol{s}_t = \left[\boldsymbol{w}_t^{1T}, \ldots, \boldsymbol{w}_t^{pT}, \boldsymbol{h}_t^{1T}, \ldots, \boldsymbol{h}_t^{sT}\right]^T$$
- System equation:
- Observation equation: $D_t = \boldsymbol{A}_t^T \boldsymbol{s}_t + v_t$ with
- Constraint: $\boldsymbol{C}\boldsymbol{s}_t = \boldsymbol{0}$ with $\boldsymbol{C} = \begin{bmatrix} -\boldsymbol{1} & & & G^{11}\boldsymbol{1} & \cdots & G^{1S}\boldsymbol{1} \\ & \ddots & & \vdots & \ddots & \vdots \\ & & -\boldsymbol{1} & G^{P1}\boldsymbol{1} & \cdots & G^{PS}\boldsymbol{1} \end{bmatrix}$
- New observation equation: observation + constraint
  with $\boldsymbol{Y}_t = [D_t, 0, \ldots, 0]^T$ $\boldsymbol{B}_t = \begin{bmatrix} \boldsymbol{A}_t^T \\ \boldsymbol{C} \end{bmatrix}$ $\boldsymbol{v}_t = \begin{bmatrix} v_t \\ \boldsymbol{u}_t \end{bmatrix}$

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Constrained Kalman Filtering (cont'd)

- Assumptions
  $E[\boldsymbol{n}_t] = \boldsymbol{0}$ $E[\boldsymbol{n}_t \boldsymbol{n}_t^T] = \boldsymbol{Q}_t$
  $E[\boldsymbol{v}_t] = \boldsymbol{0}$ $E[\boldsymbol{v}_t \boldsymbol{v}_t^T] = \boldsymbol{R}_t = \begin{bmatrix} \sigma_t^2 & \boldsymbol{0}^T \\ \boldsymbol{0} & \end{bmatrix}$
  Tuning parameter to control how hard the constraint be satisfied
- Equations
  $$\boldsymbol{S}_t^- = \boldsymbol{S}_{t-1}$$
  $$\boldsymbol{P}_t^- = \boldsymbol{P}_{t-1} + \boldsymbol{Q}_t$$
  $$\boldsymbol{K}_t = \boldsymbol{P}_t^- \boldsymbol{B}_t^H (\boldsymbol{B}_t \boldsymbol{P}_t^- \boldsymbol{B}_t^H + \boldsymbol{R}_t)^{-1}$$
  $$\boldsymbol{S}_t = \boldsymbol{S}_t^- + \boldsymbol{K}_t (\boldsymbol{Y}_t - \boldsymbol{B}_t \boldsymbol{S}_t^-)$$
  $$\boldsymbol{P}_t = (\mathbf{I} - \boldsymbol{K}_t \boldsymbol{B}_t) \boldsymbol{P}_t^-$$

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Benefits of Constrained KF

- The constraint is taken care of automatically, and can be imposed *with varying degrees*.
- All channels are taken into account simultaneously.
  →Overlapping far-end talking is not an issue
- The AEC for each channel is updated continuously because of the constraint, even if it is inactive.
  →AEC's are always up to date
- Ambient noise can be time varying.
  → Use a separate noise tracker

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Comparison with Prior Art

- T.N. Yensen, R.A. Goubran, and I. Lambadaris, "Synthetic Stereo Acoustic Echo Cancellation Structure for Multiple Participant VoIP Conferences", IEEE Transactions on Speech and Audio Processing, Vol. 9, No. 2, pp. 168-174, Feb. 2001.
- Same: One canceller per remote channel
- Differences:
  - Constrained vs. independent cancellers
    - Additional canceller is initiated before being active
    - A canceller is updated even if it is not active
  - Frequency vs. time domain
  - KF (RLS) vs. NLMS

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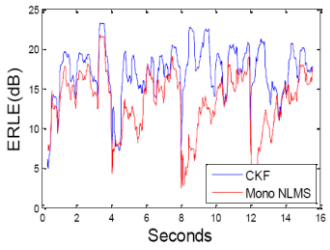
Experimental Results

- Simulation setup:
  - 4 remote talkers at [-30˚, 30˚, 0˚, -45˚]
  - Each talks for 4s
  - Noise: -20dB
  - Fixed RIR
- Comparison
  - Constrained KF
  - Multiple mono NLMS



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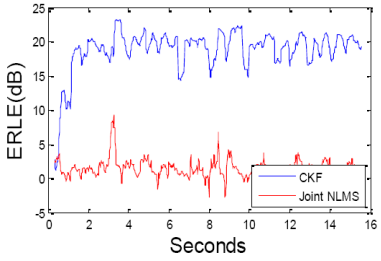
Experiment: Overlapping Talkers

- Two simultaneous remote talkers



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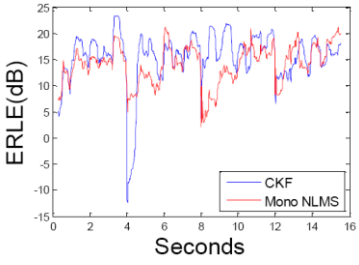
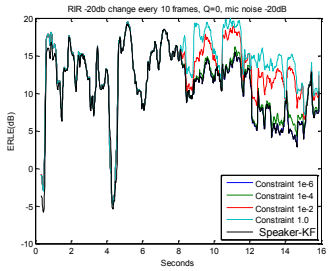
Experiment: Changing RIR

- -30dB change in RIR every 0.5 seconds

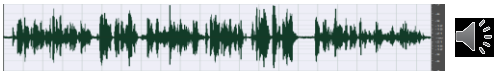


Different Constraints

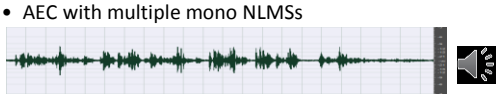


Experiment with real data

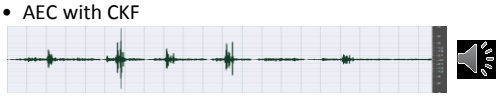
- Original recording with near-end talker



- AEC with multiple mono NLMSs

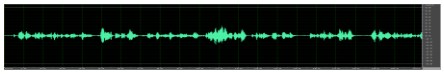


- AEC with CKF

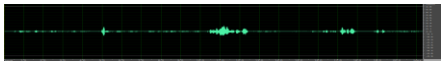


Experiment with real data (2)

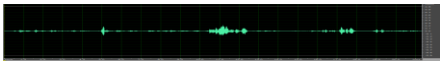
- Original Mic Input with Near-end Speech



- AEC with Far-end Channel based CKF



- AEC with Speaker Based KF



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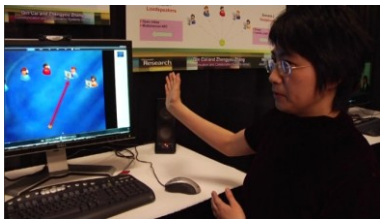
Demo Video



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Outline

- Introduction
- Sound source localization with compact mic arrays
- Spatial sound and multi-channel echo cancellation
- Video-based tracking
  - Multi-camera head pose tracking
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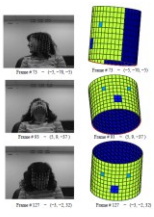
- Other video processing techniques
- Conclusions and future work

Motivation

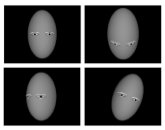
- Head Pose is very important for tele-conferencing
  - Face Relighting
  - Gaze Correction
  - Adaptive Displays
  - Video driven avatar animation, etc.

Single Camera Head Pose Tracking

- Model-based (see Lepetit 05 for a survey)



Cylinder (Aggarwal 05)



Ellipsoids (Moon 01)

3D face model (Wang 06, Vacchetti 04)

Motivation

- Single Camera Tracking has limitation on
  - Narrow Range of Tracked Poses
  - Occlusions
- Multiple Camera Tracking
  - Existing Setup in Video Conferencing
  - Multiple Views of the Face

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Challenges

- Our Multi-Cam Tracking System
  - No Pre-calibration of Camera Placements
  - Real Time Processing
  - Drift Free
  - Wider Range of Tracked Poses
  - Continuous Tracking w/ Occlusion
  - Recover after Tracking is Lost

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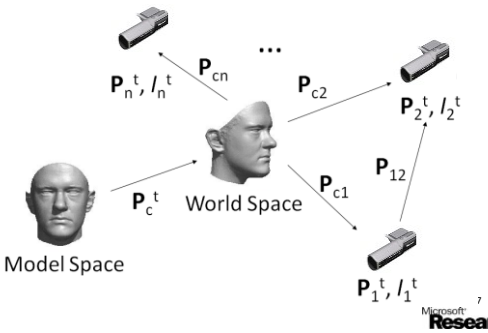
Model-based Approach



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Tracking by References

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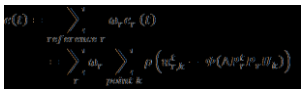
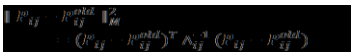
Generic Tracking Scheme

- Suitable for both single and multiple cameras
- References span on both Temporal and Spatial domains



- Camera Relative Geometry converges over time



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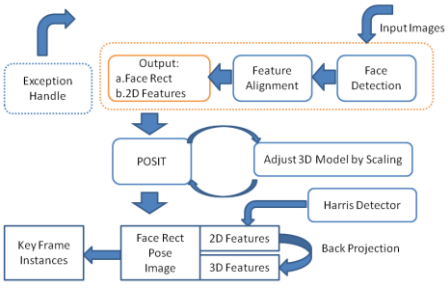
Tracking Initialization



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Tracking Algorithm

- **Input: Image , previous frames , & key frames**
- **Output: Current Pose .**
  - Select Pose of Reference frames on each camera
  - Initialize Relative Pose between Ref Camera *c* and other camera *i* .
  - For each camera *I*, do
    - *For each pose of ref. frame , do*
    - *Find 2D feature matches between and , then back-project in to get 3D points in the model **U**.*
    - *Discard outliers by applying **RANSAC***
    - *end*
  - Apply POSIT for all inlier 3D-2D matches
  - End

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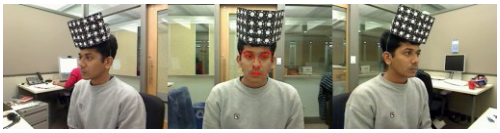
Results (3 Cameras)



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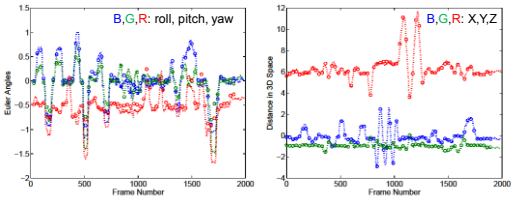
Comp. w/ Ground Truth I (No Occlusion)



….. Tracked Pose from our Algorithm.
o Ground Truth from Calibration.

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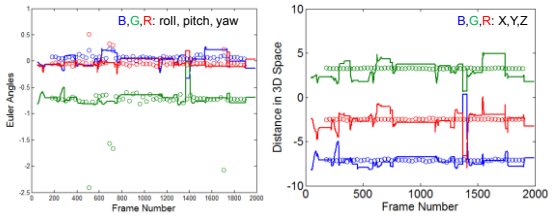
Relative Pose Comp. w/ Ground Truth II



Results (Occlusion)

Fair Comparison (no Occlusion)

# of Cams	Median Angle Error (degree)	Median Translation Error	Mean Angle Error (degree)	Mean Translation Error
1	5.9754	0.4138	19.0132	0.5504
2	5.4878	0.3481	11.8039	0.4885
3	4.4671	0.3404	11.0915	0.4634
3 (w/ pre camera calibration)	4.0827	0.3132	11.0577	0.4540

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Deformable Face Tracking

- Many applications
  - Human computer interaction
  - Performance-driven facial animation
  - Face recognition
- Challenging
  - Limited number of features on the face
  - Dozens of parameters to estimate

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Related Works

- Video based fitting
  - Active appearance models (AAM) (Xiao04)
  - 3D morphable models (Blanz99)
  - 3D deformable model + active shape model (ASM) (Vogler07)
  - Feature based (Zhang08)
- 3D scans based fitting
  - Iterative closest point (ICP) + 3D deformable model (Zhang04, Wang04, Weise09, Weise11)

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Commodity Depth Cameras

SwissRanger

Canesta

ZCam

Kinect

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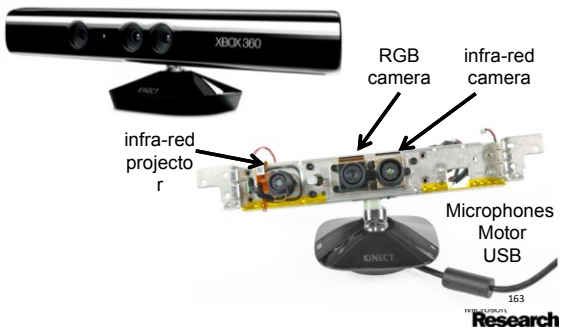
Kinect Sensor



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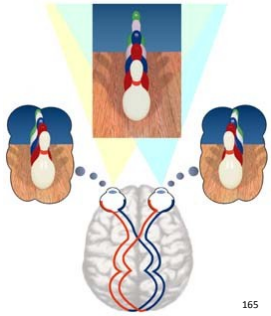
Non-commercial Windows software development kit

Access to deep Kinect system information

- Depth data
- Audio
- Direct control of the Kinect sensor
- System API

Human Stereo Vision

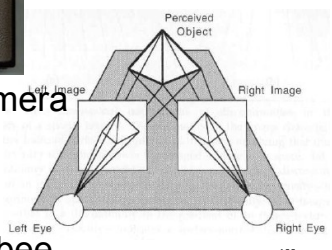
Difference in your two eyes gives you the ability to perceive your surrounding environment in **3 Dimensions**



Computer Stereo Vision

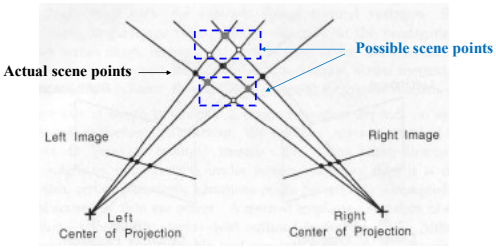
dak Stereo Camera

ntGrey Bumblebee

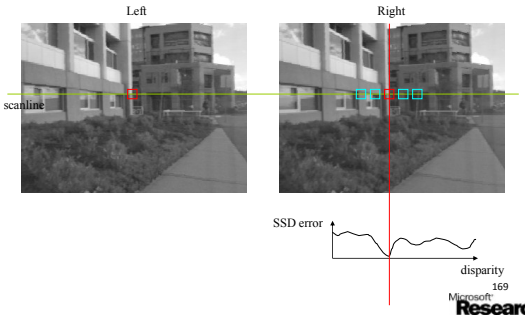


Stereo Images

Correspondence Problem

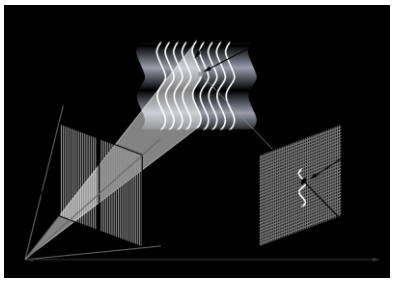


Correspondence by Correlation



How it works?

- **Structured light 3D scanner**



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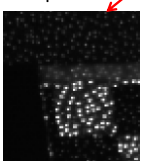
How it works? **Kinect Sensor**

- Modified structured light 3D scanner
  - IR projector
  - IR camera
  - Random pattern



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Matching & Depth Map

- Correlation

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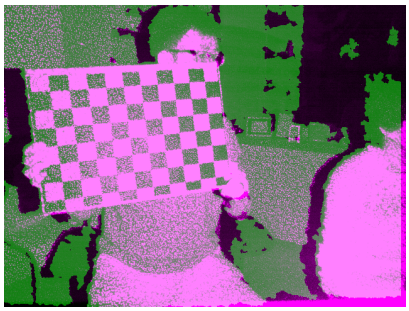
Overlay of Depth Map on IR Image



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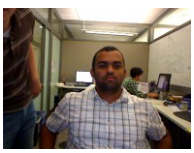
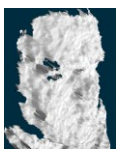
Captured Image



Texture

Depth



Depth enlarged

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Challenge and Solution

- Depth information should help tracking
- Challenge: noisy depth input
- Solution:
  - Maximum likelihood solution with arbitrary noise covariance matrices
  - Regularization

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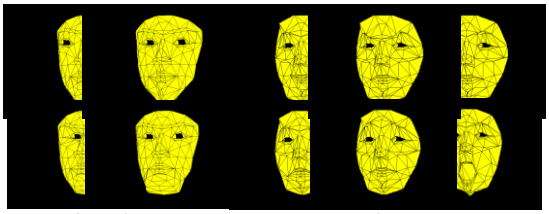
Linear Deformable Model



Static deformations Action deformations

(**Artist rendered** linear deformable model)

$$\begin{bmatrix} q_1 \\ \vdots \\ q_K \end{bmatrix} = \begin{bmatrix} p_1 \\ \vdots \\ p_K \end{bmatrix} + \boldsymbol{A}\begin{bmatrix} r_1 \\ \vdots \\ r_K \end{bmatrix} + \boldsymbol{B}\begin{bmatrix} s_1 \\ \vdots \\ s_K \end{bmatrix}, \text{ where } \boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_1 \\ \vdots \\ \boldsymbol{A}_K \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} \boldsymbol{B}_1 \\ \vdots \\ \boldsymbol{B}_K \end{bmatrix}$$

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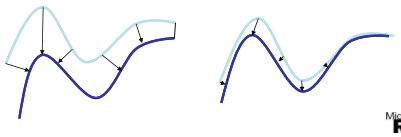
Maximum Likelihood DMF

- Formulation, $(\boldsymbol{q}_k, \boldsymbol{g}_k)$ correspondence pair:

$$\boldsymbol{R}(\boldsymbol{p}_k + \boldsymbol{A}_k\boldsymbol{r} + \boldsymbol{B}_k\boldsymbol{s}) + \boldsymbol{t} = \boldsymbol{g}_k + \boldsymbol{x}_k$$
$$\boldsymbol{x}_k \sim N(\boldsymbol{0}, \boldsymbol{\Sigma}_{\boldsymbol{x}_k})$$

- Iterative closest point
  - Assume closest points correspond
  - Compute transformation
  - Iterate until convergence



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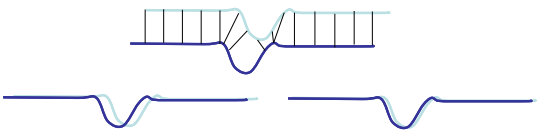
Point-to-Point and Point-to-Plane Distance



point-to-point (slow convergence) point-to-plane (fast convergence)

- In both cases, we have solution for arbitrary noise covariance matrix $\boldsymbol{\Sigma}_{\boldsymbol{x}_k}$
  - See paper for details

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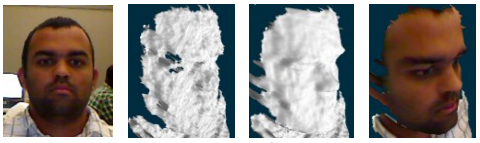
Model Initialization

- Initialization
  - Assume multiple neutral face frames available
  - Action deformations set to zero
  - Jointly solve shape deformations and rotation/translation of each frame



single frame | 30 frames aligned and averaged | textured model

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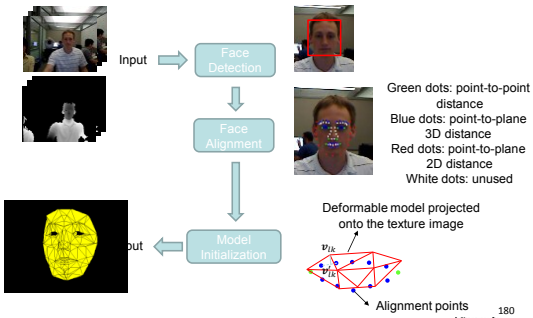
Model Initialization



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Face Tracking

- Tracking
  - Shape deformations fixed
  - Based on feature point correspondence
  - Solve for action deformation, rotation and translation
  - Regularization
    - l_2 norm constraining the difference between neighboring frames' action deformations
    - l_1 norm constraining the number of non-zero action deformation parameters

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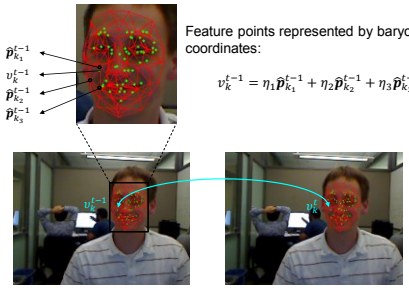
Face Tracking



Feature points represented by barycentric coordinates:

$$v_k^{t-1} = \eta_1 \hat{p}_{k_1}^{t-1} + \eta_2 \hat{p}_{k_2}^{t-1} + \eta_3 \hat{p}_{k_3}^{t-1}$$

Texture image at time t-1 | Texture image at time t

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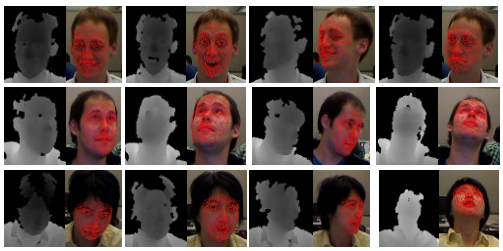
Tracking Results



Top to bottom: Seq #1 (810 frames), Seq #2 (681 frames), Seq #3 (300 frames)

Video

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Qualitative Results

Median tracking error in pixels

	ID+l_2	ID+l_1	ID+l_2+l_1	NM+l_2	NM+l_1	NM+l_2+l_1
Seq #1	3.56	2.88	2.78	2.85	2.69	2.66
Seq #2	4.48	3.78	3.71	4.30	3.64	3.55
Seq #3	3.98**L**	3.91	3.91	3.92**L**	3.91	3.50

ID: use identity covariance matrix for sensor noise
NM: use the proposed noise modeling scheme
l_2: quadratic constraint between successive frames
l_1: sparse constraint on the action transforms
L: lost tracking in the middle and never recover

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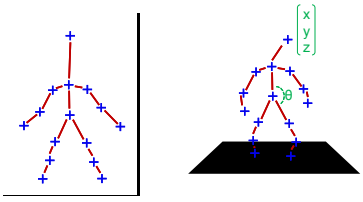
Human Pose Estimation



Kinect tracks 20 body joints in real time.

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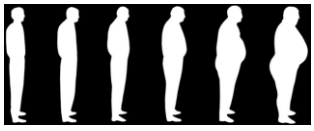
Why Is It Hard?

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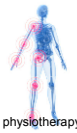
Why Do We Want It?

interaction

analysis




And applications to be determined…

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Motion Capture


[Vicon]


[Xsens]

- ☑ very accurate
- ☑ high frame rate
- ☒ suit / sensors
- ☒ expensive
- ☒ large space
- ☒ calibration

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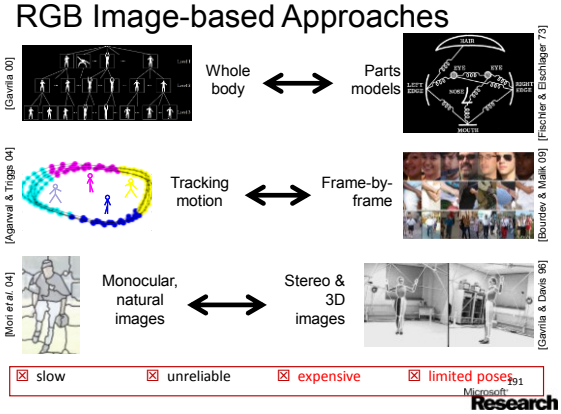
RGB Image-based Approaches



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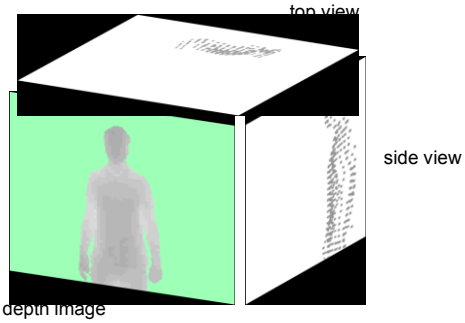
Depth Cameras



Microsoft Research

RGB vs. Depth for Pose Estimation

RGB

- ☒ Only works well lit
- ☒ Background clutter
- ☒ Scale unknown
- ☒ Clothing, skin colour

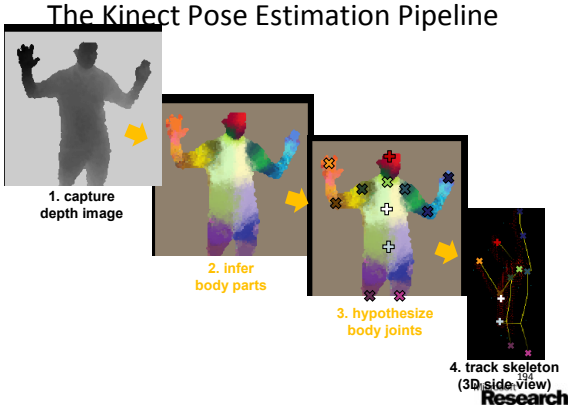
much easier with depth!

DEPTH

- ☑ Works in low light
- ☑ Person 'pops' out from bg
- ☑ Scale known
- ☑ Uniform texture
  - ☑ easy to simulate
- ☒ Shadows, missing pixels

Microsoft Research

The Kinect Pose Estimation Pipeline



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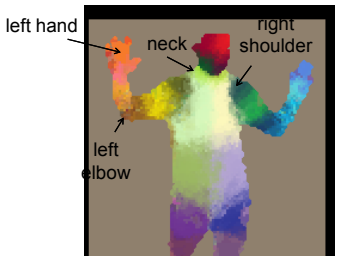
Body Part Recognition



("left" = player left with camera acting as mirror)

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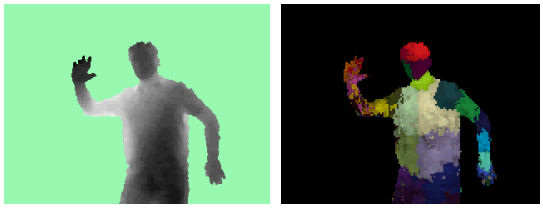
Body Part Recognition

- No temporal information
  - Frame-by-frame
- Local pose estimate of parts
  - Independently treat
    - Each pixel & each body joint
  - Reduces training data and computation time
- Very fast
  - Depth image features
  - Decision forest classifier

Microsoft Research

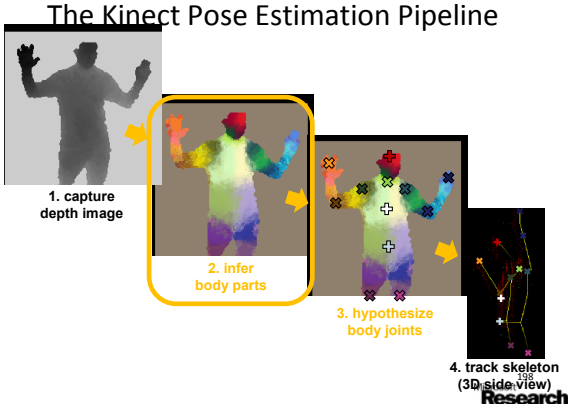
Body Part Recognition



input depth image | inferred body parts

Microsoft Research

The Kinect Pose Estimation Pipeline



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Classifying Pixels

- Compute $\mathrm{P}(c_i \mid w_i)$
  - pixels $i = (x, y)$
  - body part c_i
  - image window w_i

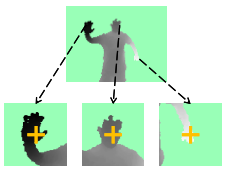

image windows move with classifier

- Discriminative approach
- Learn classifier $\mathrm{P}(c_i \mid w_i)$ from training data

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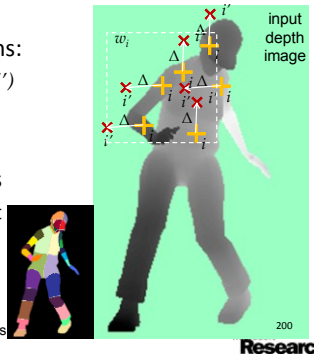
Fast Depth Image Features

- Depth comparisons:
  - $f(i\,;\,\Delta) = d(i) - d(i')$ where $i' = i + \Delta$
- Background pixels
  - d = large constant



desired
body parts

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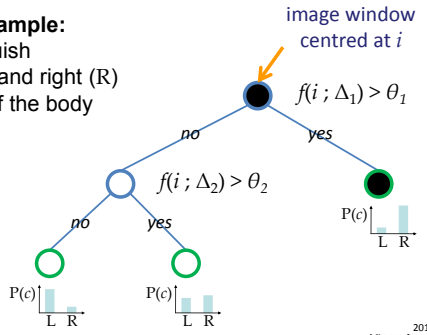
Decision Tree Classification

Toy example:
distinguish
left (L) and right (R)
sides of the body



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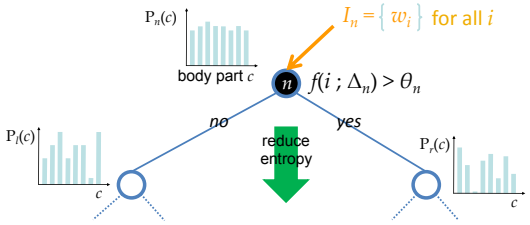
Training Decision Trees (Breiman 84)



Take (Δ, θ) that maximises information gain:

$$\Delta E = -\frac{|I_l|}{|I_n|}E(I_l) - \frac{|I_r|}{|I_n|}E(I_r)$$

Goal: drive entropy at leaf nodes to zero

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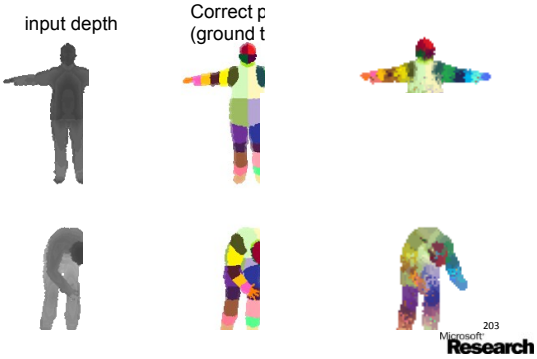
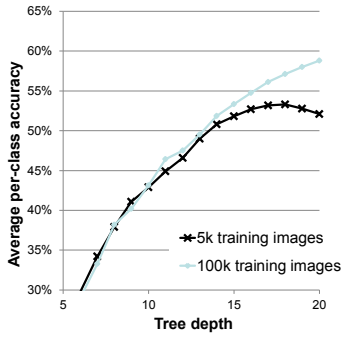
Depth of Trees



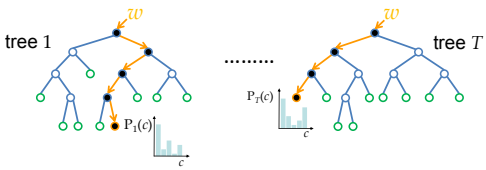
Depth of Trees



Decision Forests

(Amit 97, Breiman 01, Geurts 06)

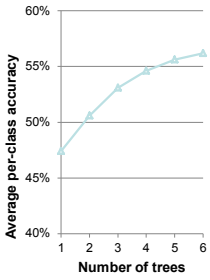
- Single trees tend to over-fit
- Train forest – ensemble of trees:



  - different random subset of images
  - average tree posteriors

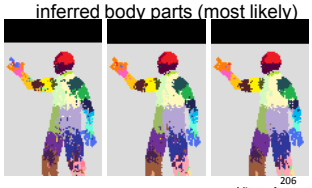
$$P(c|w) = \sum_{t=1}^{T} P_t(c|w)$$

Number of Trees



th

inferred body parts (most likely)



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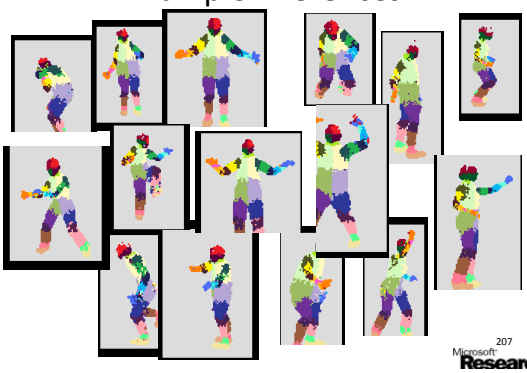
Example Inferences



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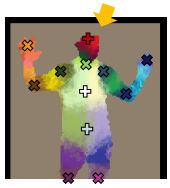
Body Parts to Joint Hypotheses

- Depth image & probability mass
- Localize body parts in 3D
  - global centroid of prob. mass
  - local modes of density (mean shift)
- Map body parts to skeletal joints
  - many parts map directly to joints



3. hypothesize body joints

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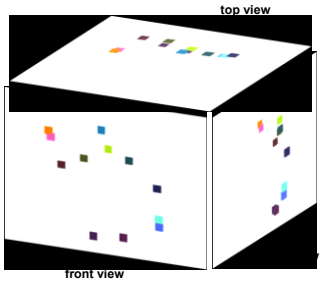
3D Joint Hypotheses

NB No tracking or smoothing!

input depth image

inferred body parts & overlaid joint hypotheses



3D joint hypotheses

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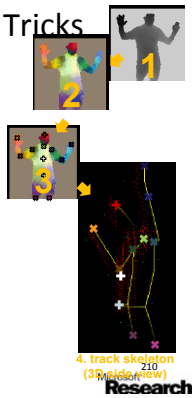
… and Some Other Tricks

- Exploit
  - 3D joint hypotheses
  - kinematic constraints
  - temporal coherence
- Predict
  - full skeleton
  - invisible joints
  - multi-player



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Outline

- Introduction
- Sound source localization with compact mic arrays
- Spatial sound and multi-channel echo cancellation
- Video-based tracking
- Other video processing techniques
  - Learning-based perceptual image quality enhancement
  - Monocular 3D and Foreground/background segmentation
  - Joint tracking and multiview video compression
- Conclusions and future work

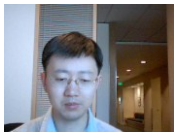
Motivation

- Two factors affecting image quality during video conferencing:
  - Camera device
  - Lighting condition
- Observation
  - Camera devices are getting better
  - Lighting conditions will stay the same
- Goal:
  - Improving virtual lighting condition

Previous work

- Brightness and contrast improvement
  - Hardware:
    - Automatic gain control
    - Face tracking -> gain control parameters
  - Image processing techniques (exposure correction):
    - Bhukhanwala 94, Messina 03, Saitoh 99, Shi 04

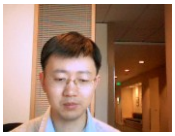
Beyond exposure



Original

Good exposure

But pale, unpleasant



Enhanced

Warm, appealing

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Color tone

- Stage lighting design
  - Color scheme is critical
    - The perceived look of the host / actors
    - Mood of the stage
- How does a color affect the look of a face
  - Subjective
  - No mathematical formula
  - Learning from experts

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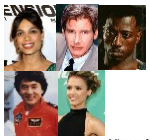
Learning-based color tone mapping

- Idea:
  - Learning color statistics from images taken by professional photographers (in good lighting conditions)
  - Color tone mapping for an input image
- Data collection:
  - 400 celebrity images



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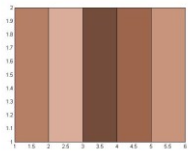
Training

- Mixtures of Gaussians
  - Feature:
    - mean and variance on the face region
      $v_i = (m_{i,r}, m_{i,g}, m_{i,b}, \sigma_{i,r}, \sigma_{i,g}, \sigma_{i,b}), i = 1,\ldots,400$
    - 5 mixture components $(\mu_j, \Sigma_j), j = 1,\ldots,5$



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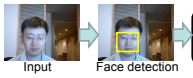
Color tone mapping



Source mean/std vector
$v = (m_1, m_2, m_3, \sigma_1, \sigma_2, \sigma_3)$

Target mean/std vector= weighted sum of cluster centers
$\bar{v} = (\bar{m}_1, \bar{m}_2, \bar{m}_3, \bar{\sigma}_1, \bar{\sigma}_2, \bar{\sigma}_3) = \sum_{j=1}^{5} w_j(v) * \mu_j$

$$w_j = \frac{1/D_j(v)}{\sum_{l=1}^{5} 1/D_l(v)}$$

$$D_j(v) = \sqrt{(v-\mu_j)^T \Sigma_j^{-1} (v-\mu_j)} \Rightarrow \text{Mahalanobis distance}$$

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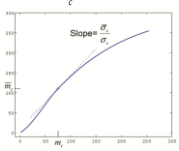
Color tone mapping function

$y = f_c(x)$: Color tone mapping function for channel c

Piecewise cubic spline with constraints:

$$f_c(m_c) = \bar{m}_c \quad f_c(0) = 0 \quad f_c(255) = 255$$

$$f_c'(m_c) = \frac{\bar{\sigma}_c}{\sigma_c} \quad f_c'(0) = 0.5\frac{\bar{m}_c}{m_c} \quad f_c'(255) = 0.5\frac{255-\bar{m}_c}{255-m_c}$$



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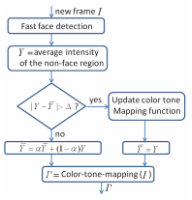
Application to video sequence

- Image intensities change over time:
  - Automatic gain control
  - Lighting change
- Global intensity change detect
  - Updating color tone mapping function whenever a global intensity change is detected



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Computation reduction

- Color table lookup:
  - Each color tone mapping functions $f_c(x)$ is stored as a color lookup table with 256 entries
  - Color tone mapping for each pixel becomes 3 simple table lookup.
- CPU usage:
  - 5% on a 3.2GHz PC with video resolution 320x240 and frame rate 30fps

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Experiment results

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User Study

- 16 video sequences
  - Offices with various lighting conditions
  - Eight different webcams
    - Logitech, Creative, Veo, Dynex, Microsoft LiveCam, etc.
- User is asked to look at the side-by-side view for each sequence, and rate each one with a MOS score:
  - 1: very bad quality
  - 2: bad quality
  - 3: acceptable
  - 4: good quality
  - 5 very good quality

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User study results

- 18 users responded
- Average improvement:
  - **2.55 ⇨ 3.30**

Sequence ID	Original Video	Enhanced Video
1	2.89	3.50
2	2.94	3. 33
3	1.94	2.67
4	1.61	2.83
5	2.11	3.00
6	3.22	4.17
7	3.11	3.72
8	1.89	2.72
9	2.11	2.17
10	1.94	2.00
11	2.11	3.44
12	3.28	3.72
13	2.65	4.18
14	2.33	3.72
15	3.00	3.89
16	3.72	3.67
Average	**2.55**	**3.30**

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Extend to Hardware Solution

- Observation:
  - Camera auto exposure responds to environment
  - Local Lighting for target (face) may not be sufficient
- Control exposure based on target
  - Extreme exposure leads to noise
  - Lack of color tone adjustment

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Our Solution

- Active lighting
  - Use computer controlled lights
  - Automatically determine the appropriate lighting to optimize face image quality

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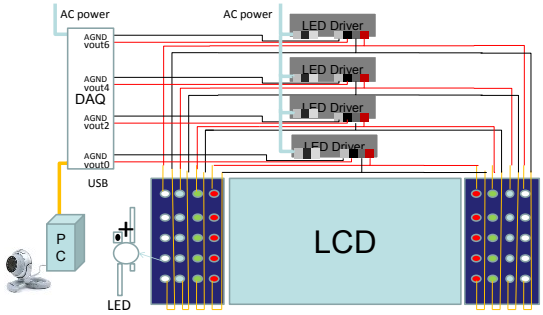
Hardware Configuration



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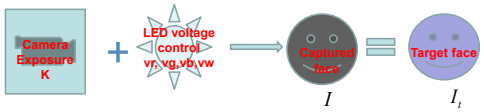
Software: Optimization Problem

- Image is a function of exposure and light



- Goal: Find the right exposure k and voltages **v** to minimize the difference between captured image and target image

$$\min_{k,\mathbf{v}} \|I(k,\mathbf{v}) - I_t\|$$

$$\mathbf{v} = [v_r, v_g, v_b, v_w]^T$$

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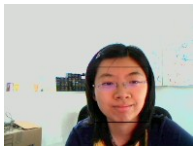
Experiment Results

Video

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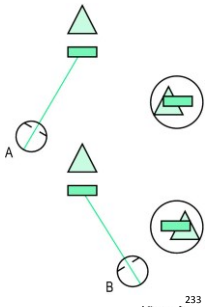
What is Motion Parallax

- Apparent difference in the direction of movement or speed produced when the subject moves relative to his environment



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Track User Movement

- Motion tracking systems (Welch and Foxlin 02)
  - Mechanical sensing
  - Inertial sensing
  - Acoustic sensing
  - Magnetic sensing
  - Optical sensing
  - Radio frequency sensing
- For our applications, we use
  - Face tracking via webcams

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Mono 3D

(Pastoor 99, Suenaga 05, Harrison 08)

- Pseudo-3D effects for teleconferencing
  - Box framing

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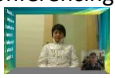
Mono 3D

- Pseudo-3D effects for teleconferencing
  - Box framing
  - Layered video



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Video Segmentation

- Very challenging problem
- Existing scheme using:
  - Stereo (Kolmogorov 05)
  - Mono video (Criminisi 06, Sun 06, Yu 07)
  - Depth camera

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Fg/Bg Segmentation with Depth Camera

- We explore the use of depth camera for live video foreground/background segmentation

ZCam system specification: Full RGB resolution: 640*480;
Operation range: 0.5-2.5 meter
Depth data rate: 30fps (320*240)

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Sample Video

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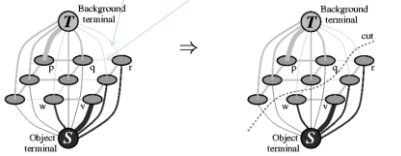
Graph-Cut Based Segmentation

- We build a graph model for graph-cut segmentation.

$$P(s|I) = \frac{1}{Z}\exp\left\{\sum_{i\in V}\sum_{k}\lambda_k\Phi_k(s_i,I) + \sum_{<i,j>\in E}\Psi(s_i,s_j,I)\right\} = \frac{1}{Z}\exp\{E(s,I)\}$$



(Boykov and Kolmogorov 03)

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The Cues for Segmentation

- ZCam provides color images, depth and depth confidence.

$$P(s|I) = \frac{1}{Z}\exp\left\{\sum_{i\in V}\sum_{k}\lambda_k\Phi_k(s_i,I) + \sum_{<i,j>\in E}\Psi(s_i,s_j,I)\right\} = \frac{1}{Z}\exp\{E(s,I)\}$$

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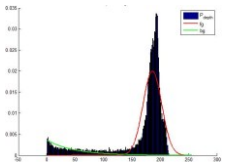
Data Term

- Data term in the graph

$$\Phi_{color}(s_i, I) = -\ln\left\{P_{color}(I_i|s_i) \cdot P_{\text{confidence}}(s_i)\right\}$$
$$\Phi_{depth}(s_i, I) = -\ln\left\{P_{depth}(I_i|s_i) \cdot P_{\text{confidence}}(s_i)\right\}$$

The color likelihood is computed from the previous segmentation mask.
The depth likelihood is generated from depth histogram.



$$P_{depth}(I_i^Z|s_i = 1) = G(I_i^Z|_{\mu,\sigma})$$

$$P_{depth}(I_i^Z|s_i = 0) = \gamma e^{-\gamma I_i^Z}$$

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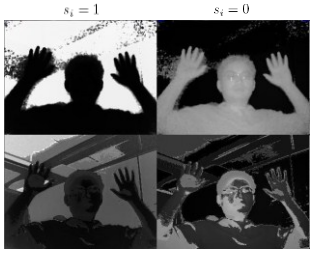
Data Term

- Data term in the graph

$s_i = 1$ $\quad$ $s_i = 0$

$\Phi_{depth}(s_i, I)$

$\Phi_{color}(s_i, I)$



$$\Phi_{color}(s_i, I) = -\ln\left\{P_{color}(I_i|s_i) \cdot P_{\text{confidence}}(s_i)\right\}$$
$$\Phi_{depth}(s_i, I) = -\ln\left\{P_{depth}(I_i|s_i) \cdot P_{\text{confidence}}(s_i)\right\}$$

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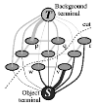
Link Term

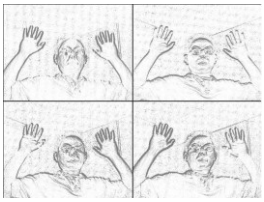
- Link term in the graph



$$\Psi(s_i, s_j, I) = [s_i \neq s_j] \cdot \frac{1}{dist(i,j)} \cdot e^{\frac{-\|I_i - I_j\|^2}{2\beta^2}}$$

Horizontal link term

Vertical link term



Diagonal link term

Diagonal link term

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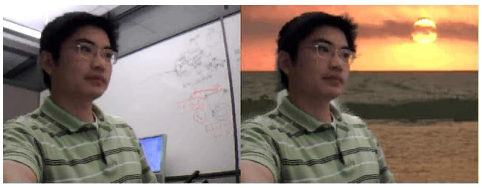
Results



Results showed with background replacement.

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Outline

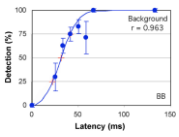
- Introduction
- Sound source localization with compact mic arrays
- Spatial sound and multi-channel echo cancellation
- Video-based tracking
- Other video processing techniques
  - Learning-based perceptual image quality enhancement
  - Monocular 3D and Foreground/background segmentation
  - Joint tracking and multiview video compression
- Conclusions and future work

Motion Parallax

- Improve 3D perception
  - More realistic 3D experience when combined with 3D displays
  - Works with legacy 2D displays

Motion Parallax Delay Sensitivity

- Rendering video from exact viewer perspective is a must. This has impact on:
  - Realism
  - 3D clues
  - Comfort/sickness
- Motion parallax should be kept below **30** ms.

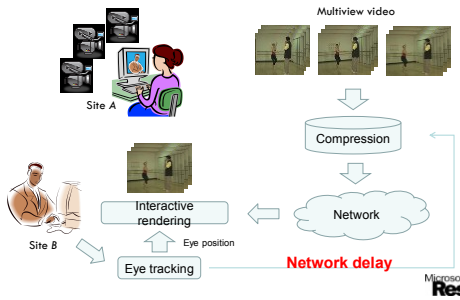


from: Stephen Ellis

- Motion Parallax based Rendering needs to be **LOCAL**.

Enable Motion Parallax for Multiview Video based 3D Teleconferencing

- Eye tracking + multiview video + view synthesis



Core Idea

- At the encoding site, predict the viewer's future viewing position
  - Encode 2 nearby frames (Kurutepe 07)
  - Rate distortion optimization (Ramanathan 07)
- Encode each region of the views with different fidelity, *depending on the its use* (weight) on final (synthesized) image at the predicted viewing position.
- At the decoding site, decompress the multiview video, and render with the user's actual viewing position

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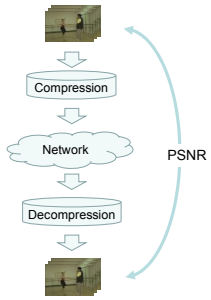
Video Compression Error Criteria

- Traditionally:
  - Input: Video
  - Output: Video
  - Measure PSNR between original frames and the decompressed frames
  - What the user sees: the decompressed frames



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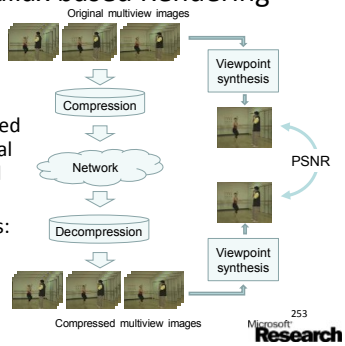
Multiview Video Compression with Motion Parallax based Rendering

- Input: Video
- Output: Video
- Measure PSNR between synthesized views of the original and decompressed videos
- What the user sees: the **synthesized** frames



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An Example Multiview Frame

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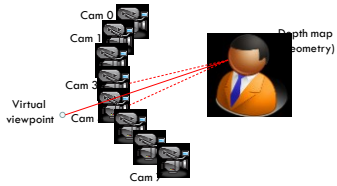
Virtual View Synthesis

We project (each pixel of) the virtual view onto the depth map. Each point is then traced back to two nearest cameras for interpolation. Occlusion is explicitly computed. (Buehler 01)



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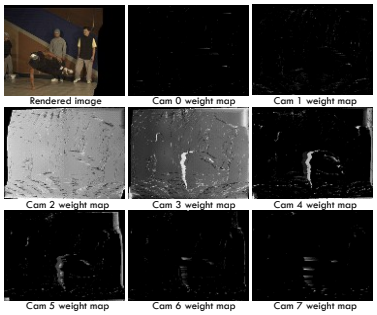
Weight Maps for Rendering



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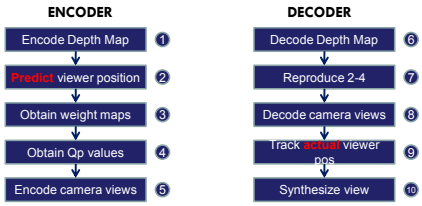
Overall Diagram



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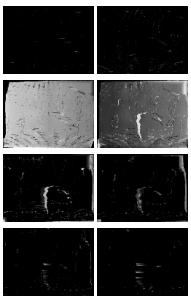
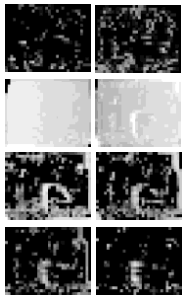
Weight Maps and Qp Maps



Weight maps



Qp maps

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Cam 2 Cam 3 Cam 4

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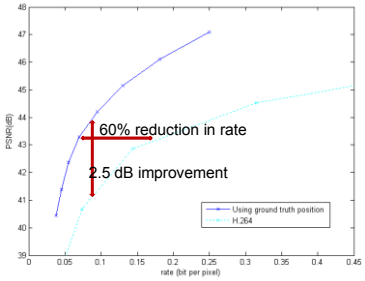
Result with Perfect Viewer Positions



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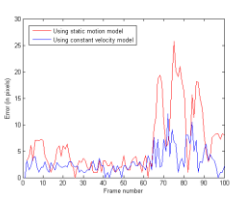
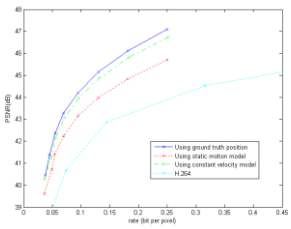
What About Prediction Errors?

- Can cause significant performance drop





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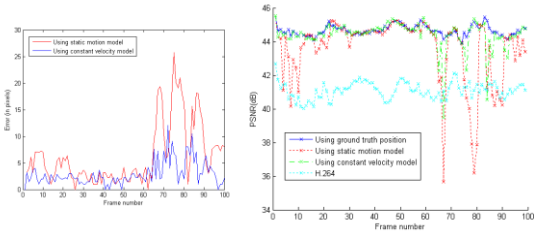
Frame-by-frame PSNR



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Particle Filter (Condensation) based Tracking (Isard 98)

- A Posteriori Probability of the object status at time t:

$$p(\boldsymbol{x}_t|\boldsymbol{Z}_t) \propto p(\boldsymbol{z}_t|\boldsymbol{x}_t)p(\boldsymbol{x}_t|\boldsymbol{Z}_{t-1})$$

$\boldsymbol{x}_t$: object status; $\boldsymbol{Z}_t$: input tracking video stream

where:

$$p(\boldsymbol{x}_t|\boldsymbol{Z}_{t-1}) = \int_{\boldsymbol{x}_{t-1}} p(\boldsymbol{x}_t|\boldsymbol{x}_{t-1})p(\boldsymbol{x}_{t-1}|\boldsymbol{Z}_{t-1})$$

assuming object dynamics follows a temporal Markov chain.

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Particle Filter (Condensation) based Tracking (Isard 98)

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$$p(\boldsymbol{x}_t|\boldsymbol{Z}_t) \propto p(\boldsymbol{z}_t|\boldsymbol{x}_t)p(\boldsymbol{x}_t|\boldsymbol{Z}_{t-1})$$

$\boldsymbol{x}_t$: object status; $\boldsymbol{Z}_t$: input tracking video stream

where: Best prediction at the encoder

$$p(\boldsymbol{x}_t|\boldsymbol{Z}_{t-1}) = \int_{\boldsymbol{x}_{t-1}} p(\boldsymbol{x}_t|\boldsymbol{x}_{t-1})p(\boldsymbol{x}_{t-1}|\boldsymbol{Z}_{t-1})$$

assuming object dynamics follows a temporal Markov chain.

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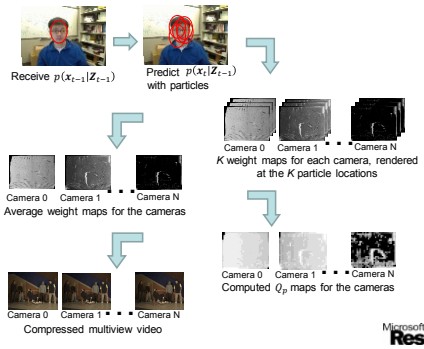
Joint Tracking and Compression



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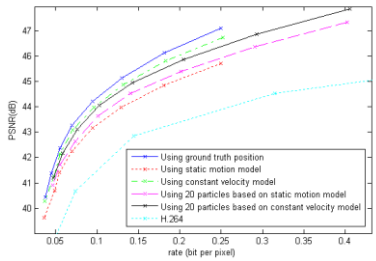
Results with Joint Tracking and Compression



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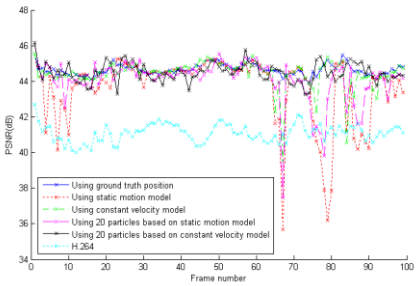
Frame-by-frame PSNR



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Frame-by-frame PSNR

Approach	Variance of PSNR (dB)
Using ground truth position	0.097
Using static motion model	3.819
Using constant velocity model	0.693
Using 20 particles based on static motion model	1.477
Using 20 particles based on constant velocity model	0.285
H.264	0.246

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Outline

- Introduction
- Sound source localization with compact mic arrays
- Spatial sound and multi-channel echo cancellation
- Real-time video processing
- Exploring depth sensors
- Conclusions and future work

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Conclusions

- Compact mic array SSL and its further improvement with room models
- Audio/visual feature level fusion for speaker detection
- Headphone/loudspeaker audio spatialization
- Multi-channel echo cancellation with Kalman filtering
- Head pose/facial expression tracking
- Depth camera based skeleton tracking
- Learning based perceptual video quality enhancement
- Motion parallax in videoconferencing
- Joint tracking and multiview compression

Future Work

- Audio
  - Audio quality assessment
  - Personal HRTF measurement
  - Mic and speaker at unknown locations
  - Distributed mic arrays
  - …
- Video
  - More reliable/accurate tracking, low computational cost
  - Understand human emotions
  - Depth image processing
  - 3D view synthesis, hybrid virtual/real environments
  - …

Acknowledgement

- Our colleagues
  - Qin Cai, Wei-ge Chen, Ross Cutler, Philip Chou, Dinei Florencio, Rajesh Hedge, Zicheng Liu, Yong Rui, Jamie Shotton, Mike Sinclair, Jay Stokes, Jian Sun, Paul Viola, etc.
- Students
  - Demba Ba, Flávio Ribeiro, Myung-Suk Song, Zhaozheng Yin, Pei Yin, Aswin C. Sankaranarayanan, Qing Zhang, David Gallup, Mingxuan Sun, etc.
- Microsoft product groups
  - Microsoft Unified Communication Group, Microsoft Interactive Entertainment Division Kinect Team, etc.

Thank you!

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