Ubiquitous Projected Light Displays

Jim Rehg

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College of Computing
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External Collaborators

- Tat-Jen Cham
  - Nanyang Technological University, Singapore

- Rahul Sukthankar
  - Compaq Cambridge Research Lab, Boston

- Gita Sukthankar
  - Compaq Cambridge Research Lab, Boston

Internal Collaborators

- Vision/HCI
  - Gregory Abowd (Faculty)
  - Jay Summet (First year PhD)
  - Matt Flagg (Senior undergraduate)
- Systems
  - Kishore Ramachandran (Faculty)
  - Yavor Angelov (First year PhD)

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Outline

- Ubiquitous displays
  - Goals and methods
  - Four subproblems
- Projector-camera calibration
- Compensating for occluders
  - Shadow elimination
  - Occluder light suppression
- Experimental results
- Conclusion and future work

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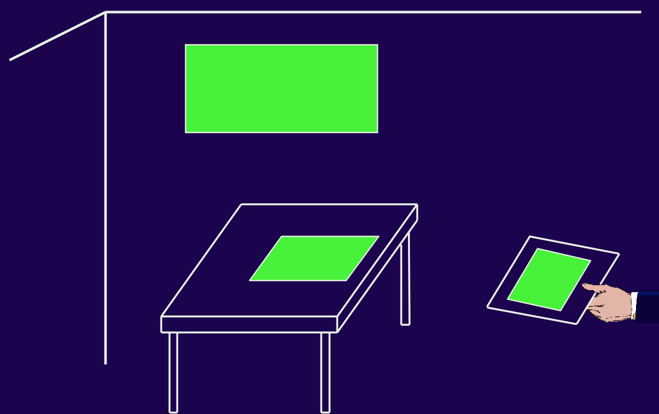
Ubiquitous Displays



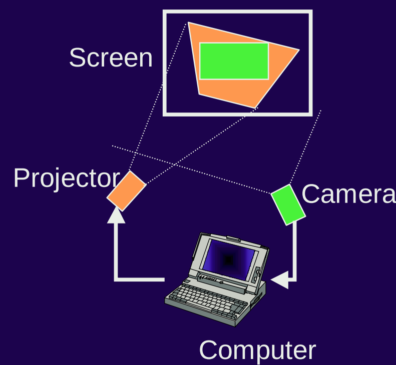
Every (planar) surface is a potential display

Ubiquitous Displays

- Displays should be:
  - Embedded in your physical environment
  - Scalable and controllable
  - Wherever you want them to be
- Advantages of projectors:
  - Flexible and scalable
  - Available and economical (price/sq foot)
- Disadvantages of projectors:
  - Hot and noisy
  - Expensive

Projected Light Display

- System of projectors and cameras which can create a stable display of an arbitrary image on any visible planar surface.
- Subproblems:
  - Calibration
    - Sukthankar et. al. '00
  - Compensation
    - Sukthankar et. al. '01
    - Cham et. al. '02
  - Rendering
  - Planning and control



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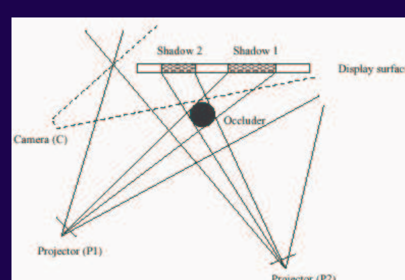

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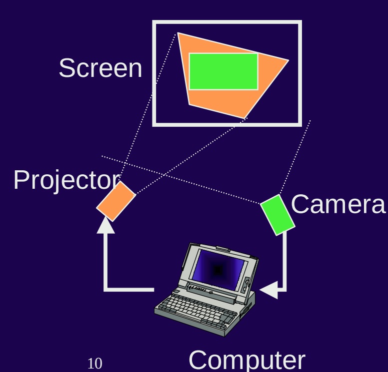
Two Key Points in Our Approach

1. No explicit 3-D calibration

System based entirely on projective mappings (homographies) between planes.



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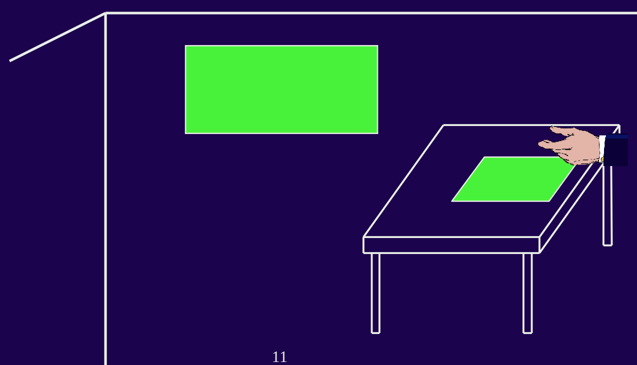
Two Key Points in Our Approach

2. No 3-D reconstruction or scene analysis

   Achieve display characteristics through visual feedback control.



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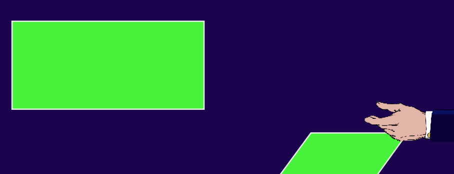

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Technical Problems

- Calibration
  - Sukthankar et. al. '00
- Compensation
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- Rendering
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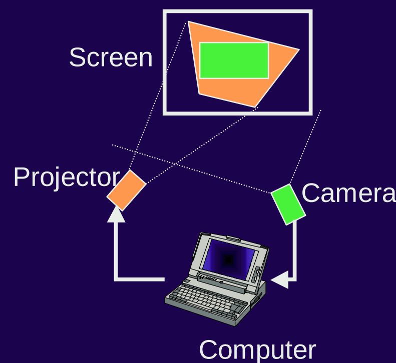
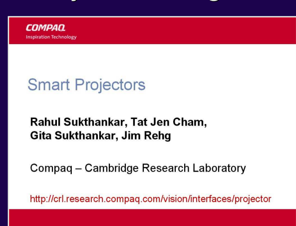


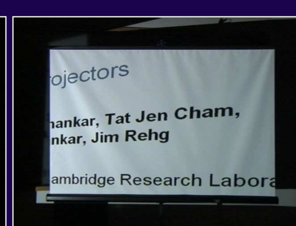
No Keystone Correction

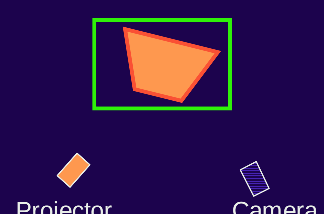
Projected image



Camera image

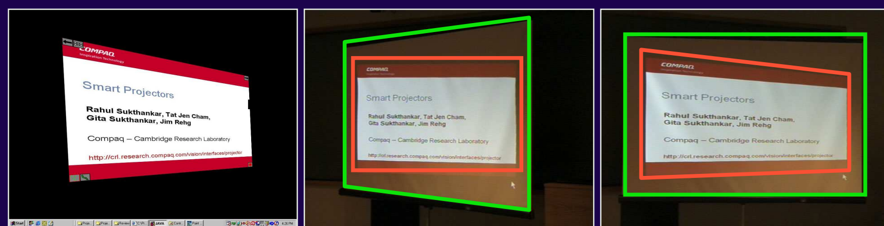
Audience sees



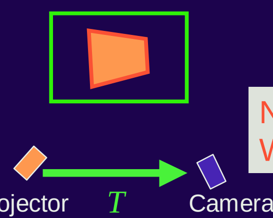


Naive Keystone Correction

Projected image | Camera image | Audience sees



T: projector-camera homography



Naive approach: Warp image by T^{-1}

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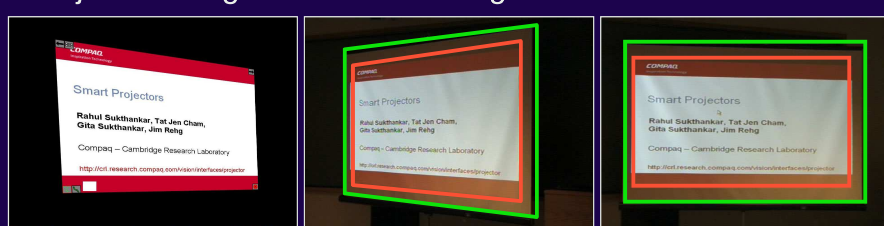
True Keystone Correction

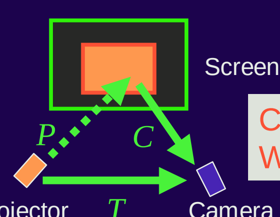
Projected image | Camera image | Audience sees



T: projector-camera homography

C: screen-camera homography

$P = C^{-1}T$



Correct solution: Warp image by P^{-1}

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Camera-Projector Homography Details

$$(x, y) = \left(\frac{p_1 X + p_2 Y + p_3}{p_7 X + p_8 Y + p_9}, \frac{p_4 X + p_5 Y + p_6}{p_7 X + p_8 Y + p_9} \right)$$

- (x,y) are coordinates of a pixel in the projector
- (X,Y) are coordinates of the same point in the camera
- (p1,p2,...p9) are the unknown parameters
- System can automatically generate pairs of {(x,y), (X,Y)}

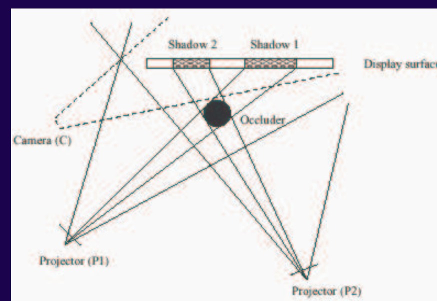
Homography Parameter Estimation

$$\begin{pmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1X_1 & -y_1X_1 & -X_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -x_1Y_1 & -y_1Y_1 & -Y_1 \\ x_2 & y_2 & 1 & 0 & 0 & 0 & -x_2X_2 & -y_2X_2 & -X_2 \\ 0 & 0 & 0 & x_2 & y_2 & 1 & -x_2Y_2 & -y_2Y_2 & -Y_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_2 & y_2 & 1 & 0 & 0 & 0 & -x_nX_n & -y_nX_n & -X_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -x_nY_n & -y_nY_n & -Y_n \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ p_9 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix}$$

- Goal: find unit vector ***p*** that best satisfies **A *p*** = **0** above
- Solution: ***p*** is the eigenvector corresponding to smallest eigenvalue of A^TA.

Technical Problems

- Calibration
  - Sukthankar et. al. '00
- Compensation
  - Sukthankar et. al. '01
  - Cham et. al. '02
- Rendering
- Planning and control



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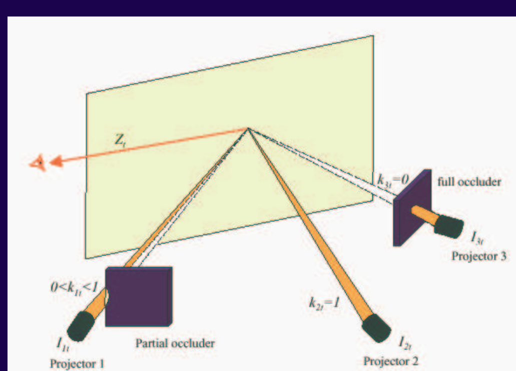
Tasks For a Single Pixel



- Measure the projected pixel value.
- Identify at least one unoccluded camera ray
- Currently using single camera, assuming all rays are unoccluded.

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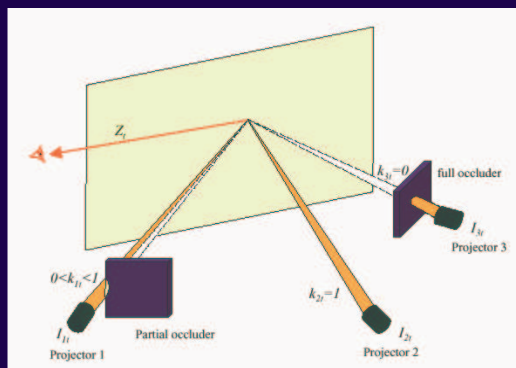
Tasks For a Single Pixel

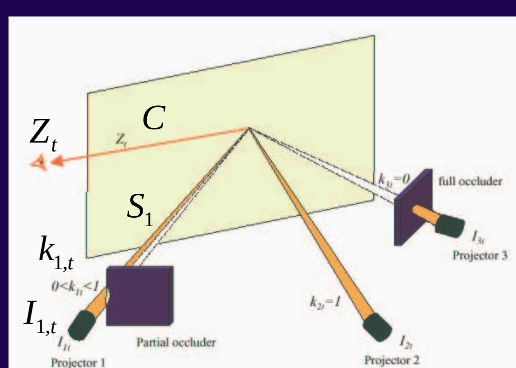


- Modify the projected pixel value.
- Identify at least one unoccluded projector ray
- Solution:
  - Probe all projectors in sequence.
  - Measure their effect on pixel.

Visual Control Loop

- Measurement Model

$$Z_t = C(k_{1,t} S_1(I_{1,t}) + k_{2,t} S_2(I_{2,t}) + \cdots + k_{n,t} S_n(I_{n,t}))$$



Visual Control Loop

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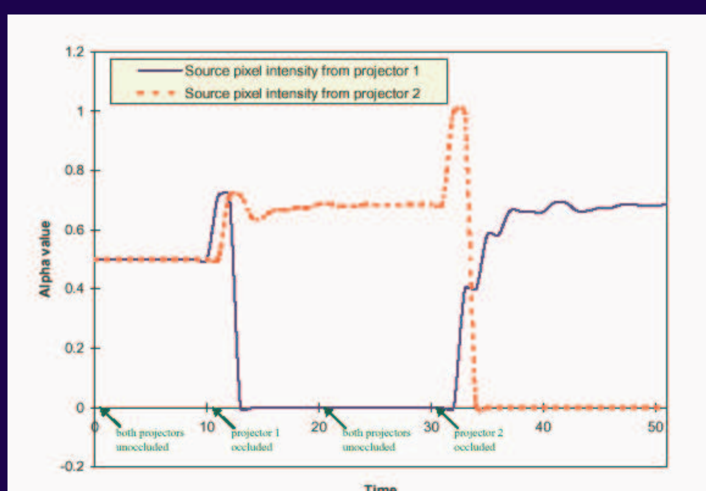
$$Z_t = C(k_{1,t}S_1(I_{1,t}) + k_{2,t}S_2(I_{2,t}) + \cdots + k_{n,t}S_n(I_{n,t}))$$

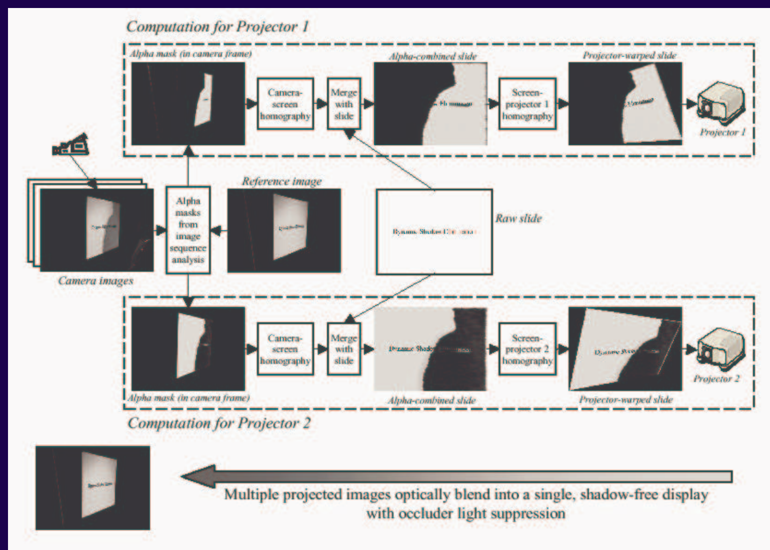
- "Actuator" Model: $I_{j,t} = \alpha_{j,t}\, I_0(Z_0)$
  - Alpha mask
- Control Law
  - Shadow Elimination: $(\Delta\alpha_{j,t})_{\mathrm{SE}} = -\gamma(Z_t - Z_0)$
  - Light Suppression: $(\Delta\alpha_{j,t})_{\mathrm{LS}} = -\beta \dfrac{(\Delta\alpha_{j,t-N})^2}{\Delta Z_{t-N}^2 + \varepsilon}$

$$\Delta Z_{t-N} = Z_t - Z_{t-N}$$

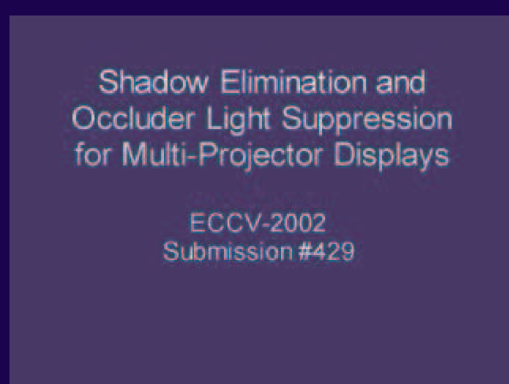
Example of System Dynamics



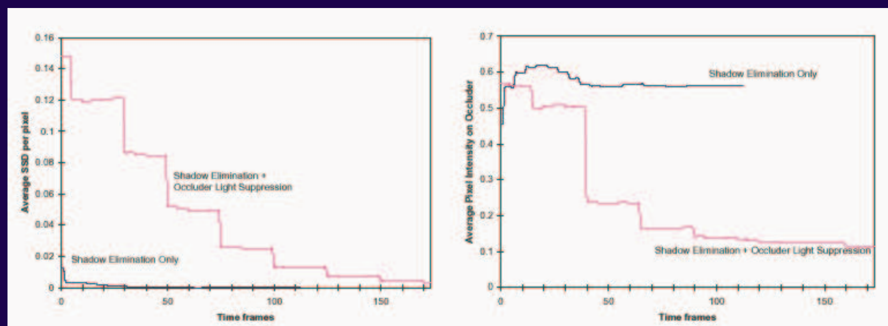
System Architecture



Experimental Results



Comparison of (SE+LS) and (SE)



(a) Shadow-Elimination Response (b) Occluder Light Response

Hysteresis effect due to LS significantly increases the robustness of the system to disturbances (moving occluders)

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Control Issues

- Obvious controls analogy
  - Observability = camera occlusions
  - Controllability = projector occlusions
- Unlike most control problems, we cannot model or measure the controllability or observability directly.
- Instead, we modulate the control (via probing) to determine the controllability properties.
- A kind of optimal control law where the cost is intensity squared and the objective is controllability
- Working with Magnus Egerstedt (ECE) on these issues (e.g. convergence proof).

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Conclusions

- It is possible to produce an occlusion-free projected display using front projection technology.
- The solution does not depend upon any explicit 3-D calibration or scene sensing.
- Lots of opportunity to enable interesting HCI research once the core system is working.
- Contributions:
  - First solution to multi-projector occlusion problem
  - Possibly a novel control problem at core of approach

Future Work

- Eliminate need for pre-stored reference image of each slide.
- Increase system speed
- Make calibration more automatic
- Correctness proof for feedback law
- Plane finding
- Parallel implementation using Stampede