Ubiquitous Projected Light Displays

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Internal Collaborators

- Vision/HCI
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  - Jay Summet (First year PhD)
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- Systems
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  - Yavor Angelov (First year PhD)

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
Every (planar) surface is a potential display

- 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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Two Key Points in Our Approach

1. No explicit 3-D calibration
   System based entirely on projective mappings (homographies) between planes.
Two Key Points in Our Approach

2. No 3-D reconstruction or scene analysis
   Achieve display characteristics through visual feedback control.
Technical Problems

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

No Keystone Correction

Projected image  Camera image  Audience sees

Smart Projectors
Rahul Sukthankar, Tat Jen Cham, Gito Sukthankar, J.M. Rehg
Campos – Cambridge Research Laboratory
**Naive Keystone Correction**

- Projected image
- Camera image
- Audience sees

$T$: projector-camera homography

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

**True Keystone Correction**

- Projected image
- Camera image
- Audience sees

$T$: projector-camera homography

$C$: screen-camera homography

$P = C^T T$

*Correct solution: Warp image by $P^{-1}$*
Camera-Projector Homography Details

\[(x, y) = \left( \frac{p_1X + p_2Y + p_3}{p_7X + p_8Y + p_9}, \frac{p_4X + p_5Y + p_6}{p_7X + p_8Y + p_9} \right)\]

- \((x,y)\) are coordinates of a pixel in the projector
- \((X,Y)\) are coordinates of the same point in the camera
- \((p_1,p_2,\ldots,p_9)\) are the unknown parameters
- System can automatically generate pairs of \{\((x,y), (X,Y)\)\}

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Homography Parameter Estimation

\[
\begin{bmatrix}
  x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1X_1 & -y_1X_1 & -X_1 \\
  0 & 0 & 0 & x_1 & y_1 & 1 & -x_1Y_1 & -y_1Y_1 & -Y_1 \\
  x_2 & y_2 & 1 & 0 & 0 & 0 & -x_2X_2 & -y_2X_2 & -X_2 \\
  0 & 0 & 0 & x_2 & y_2 & 1 & -x_2Y_2 & -y_2Y_2 & -Y_2 \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  x_n & y_n & 1 & 0 & 0 & 0 & -x_nX_n & -y_nX_n & -X_n \\
  0 & 0 & 0 & x_n & y_n & 1 & -x_nY_n & -y_nY_n & -Y_n \\
\end{bmatrix}
\begin{bmatrix}
p_1 \\
p_2 \\
p_3 \\
p_4 \\
p_5 \\
p_6 \\
p_7 \\
p_8 \\
p_9 \\
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

- Goal: find unit vector \(p\) that best satisfies \(Ap = 0\) above
- Solution: \(p\) is the eigenvector corresponding to smallest eigenvalue of \(A^TA\).
Technical Problems

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

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.
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

- Measurement Model
  \[ Z_t = C \left( k_{1,t} S_1(I_{1,t}) + k_{2,t} S_2(I_{2,t}) + \cdots + k_{n,t} S_n(I_{n,t}) \right) \]

- “Actuator” Model: \[ I_{j,t} = \alpha_{j,t} I_0(Z_0) \]
  - Alpha mask

- Control Law
  - Shadow Elimination: \[ (\Delta \alpha_{j,t})_{SE} = -\gamma (Z_t - Z_0) \]
  - Light Suppression: \[ (\Delta \alpha_{j,t})_{LS} = -\beta \frac{(\Delta \alpha_{j,t-N})^2}{\Delta Z_{t-N}^2 + \epsilon} \]
  \[ \Delta Z_{t-N} = Z_t - Z_{t-N} \]

Example of System Dynamics

J. M. Rehg © 2002
System Architecture

Experimental Results

Shadow Elimination and Occluder Light Suppression for Multi-Projector Displays

ECCV-2002 Submission #429
Comparison of (SE+LS) and (SE)

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

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).
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