Image Processing
6.111 Guest Lecture

Victor Tom, Sc.D.
Chief Scientist
Sensor Processing & Exploitation Tech Group
BAE Systems Technology Solutions

Overview

- Useful Image Processing Approaches

Overview

- Application of Image Processing to Major League Baseball Pitch-Tracking

Useful Image Processing Approaches

- Lighting Considerations
- Thresholding
- Morphological Filtering
  - Basic operations
  - Size sorting
  - Skeletonization
  - Greyscale morphological filtering
- Correlation
  - Object detection in imagery
  - Time delay estimation for signals

Lighting and Color

- Use good even illumination
  - Imagery less noisy and thresholding is easier
- Use of color for green screen or object tracking
  - Use well-lit saturated color for robust extraction
  - Use of color gels can increase contrast

Thresholding

- Utilize 8-bit grayscale histogram to separate foreground objects from background
- Iterative algorithm for thresholding

  Step 1: Scale image values to fill 8-bit dynamic range

  Step 2: Choose an initial threshold $T = T_0$

  Step 3: Partition image using T into two regions – background and foreground (object)

  Step 4: Compute mean gray values μ_1 and μ_2 of background and object regions respectively

  Step5: Compute new threshold $T = (\mu_1 + \mu_2)/2$

  Step6: Repeat Steps 3 thru 5 until there is no significant change in T

Sobel Operator for Edge Detection

- Operator uses two 3x3 kernels which are convolved with input image – one for horizontal derivative and one for vertical

$$G_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} * A \qquad G_y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{bmatrix} * A$$

$$G = \sqrt{G_x^2 + G_y^2}$$

Sobel Example

Input Image

Sobel Gradient

Binary Morphology

- Basic idea is to probe an image with a simple, pre-defined shape (structuring element or kernel), drawing conclusions on how this shape fits or misses the shapes in the image
- Basic operators
  - Erosion $A \ominus B = \bigcap_{b \in B} A_{-b}$
  - Dilation $A \oplus B = \bigcup_{b \in B} A_{b}$
  - Opening $A \circ B = (A \ominus B) \oplus B)$
  - Closing $A \bullet B = (A \oplus B) \ominus B)$

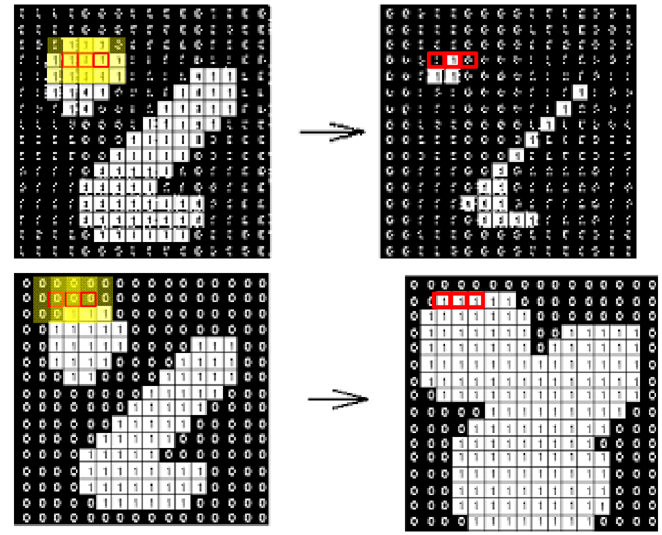
Examples of Erosion and Dilation

- Erosion

  3x3 SE

- Dilation

  3x3 SE



Examples of Opening and Closing

- Opening

  3x3 SE

```
0 0 0 0 0 0 0 0 0 0 0        0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 0 0 1 1 0 0        0 0 0 0 0 0 0 0 0 0 0
0 0 0 1 0 0 0 1 1 1 0        0 0 0 0 0 0 0 0 0 0 0
0 0 0 1 1 1 0 0 0 0 0  --->  0 0 0 1 1 1 0 0 0 0 0
0 0 0 1 1 1 0 0 0 0 0        0 0 0 1 1 1 0 0 0 0 0
0 0 0 1 1 1 0 0 0 0 0        0 0 0 1 1 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0        0 0 0 0 0 0 0 0 0 0 0
```

Removes noise

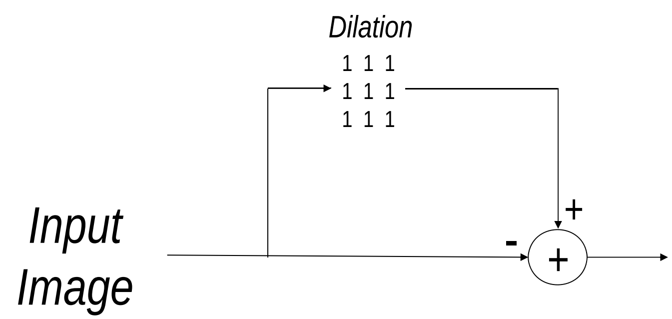
- Closing

  3x3 SE

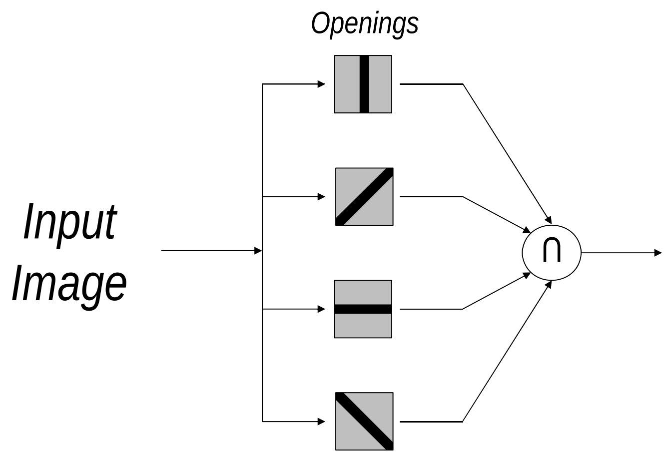
```
0 0 0 0 0 0 0 0 0 0 0        0 0 0 0 0 0 0 0 0 0 0
0 0 0 1 1 1 1 1 0 0 0        0 0 0 1 1 1 1 1 0 0 0
0 0 0 1 0 0 0 1 0 0 0        0 0 0 1 1 1 1 1 0 0 0
0 0 0 1 1 1 0 1 0 0 0  --->  0 0 0 1 1 1 1 1 0 0 0
0 0 0 1 1 1 1 1 0 0 0        0 0 0 1 1 1 1 1 0 0 0
0 0 0 1 1 1 1 1 0 0 0        0 0 0 1 1 1 1 1 0 0 0
0 0 0 0 0 0 0 0 0 0 0        0 0 0 0 0 0 0 0 0 0 0
```

Fills in holes

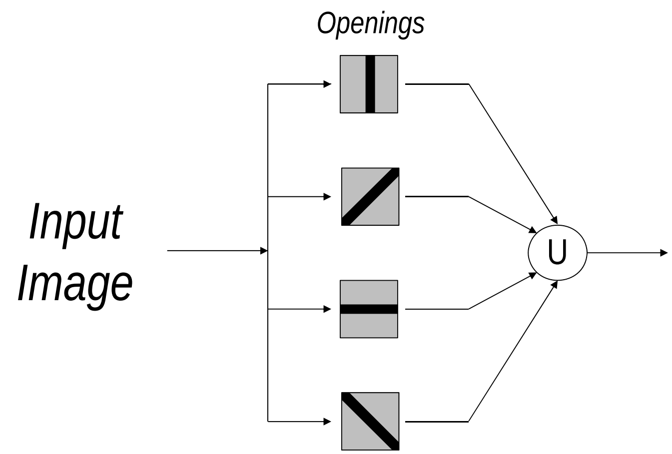
Binary Edge Detection



Composite Filter for Removing Thin Lines & Noise



Composite Filter for Removing Compact Objects Smaller than Kernel



Taking Advantage of Geometric Structure

- Objects of a known size
- Objects of a known width and length
- Lines at a particular orientation
- Shapes at a set orientation

Hit or Miss Operator

- If the foreground (1) and background (0) pixels in the structuring element *exactly match* foreground and background pixels in the image, then the image pixel underneath the origin of the structuring element is set to background (zero). Otherwise it is left unchanged

0	0	0
	1	
1	1	1

Skeletonization

- At each iteration, the image is first thinned by the left hand structuring element, and then by the right hand one, and then with the remaining six *90°* rotations of the two elements. The process is repeated in cyclic fashion until none of the thinnings produces any further change.

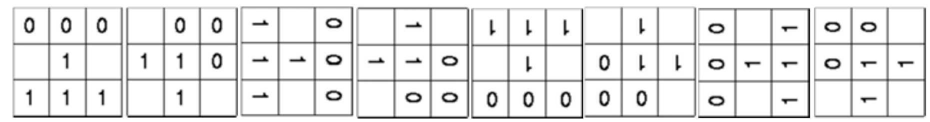
0	0	0
	1	
1	1	1

	0	0
1	1	0
	1	

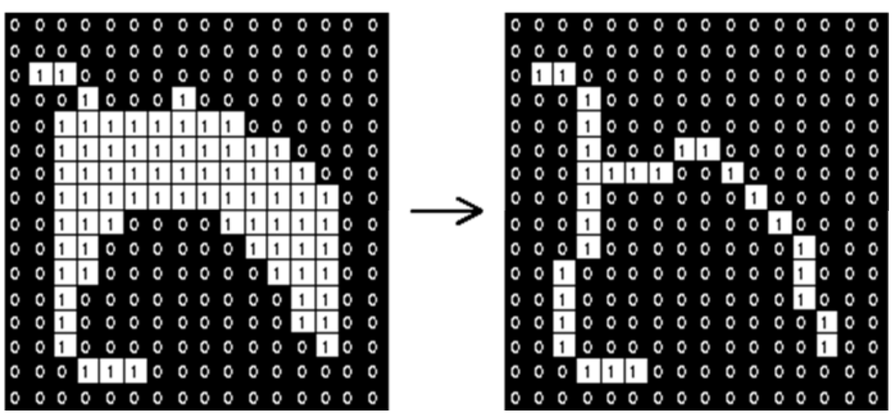
Skeletonization Structuring Elements

Skeletonization

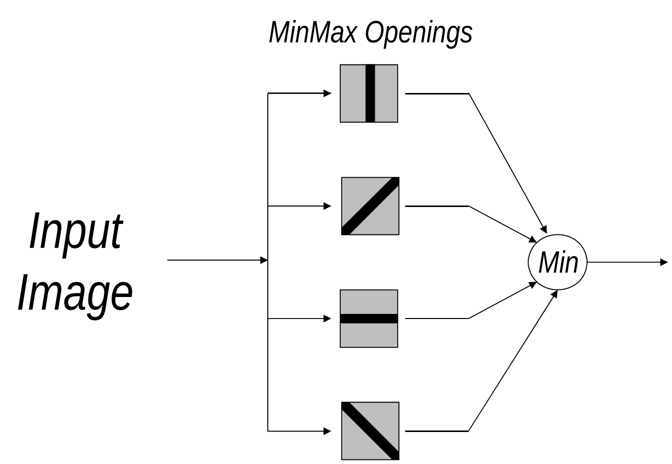
- Thin by the 8 hit-or-miss operators iteratively



Skeletonization Example



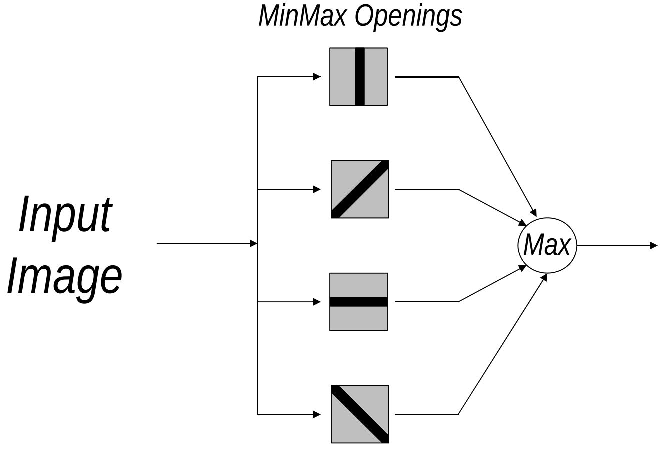
Composite Greyscale Filter for Removing Thin Lines & Noise in Any Direction



Original Image

Composite Greyscale Filter for Removing Thin Lines & Noise in Any Direction

Composite Filter for Removing Compact Objects Smaller than Kernel in All Directions



Original Image

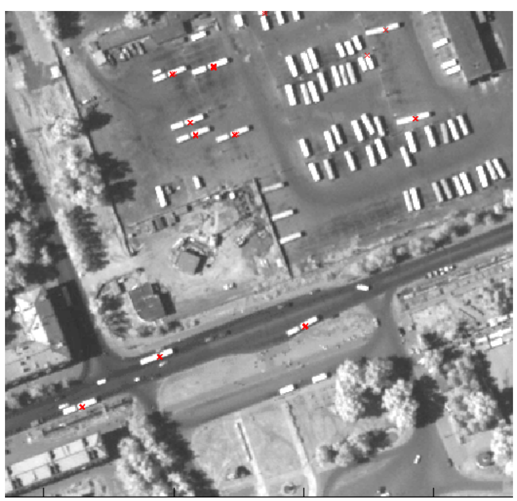
Composite Filter for Removing Compact Objects Smaller than Kernel in All Directions

Correlation for Object Detection

- Use known shape of object to generate multiple reference instances at different orientations
- Use 2D correlation to detect objects in imagery

Cross-Correlation Object Detection Example

Shape Templates



Signal Correlation for Time Delay Estimation

- Source signal provides reference signal
- Cross-correlating reference signal to delayed signals generates time-offset delay
- Applications
  - EKG R-R interval (corresponds to heart rate)
  - Acoustic signals from microphone array

Baseball Pitch Tracking

Outline

- A little history
- Problem space
  - Ball characteristics
  - Venues
- Technical Approach
  - Passive video
  - Efficient image processing for ball extraction
  - Camera model-based approach for 3-D ball positions
  - 3-D Track estimation using 3-D ball positions
- How MLB currently uses the system
  - Training and grading umpires
  - Entertaining content for www.mlb.com "gameday"

What do these have in common?

A Little History

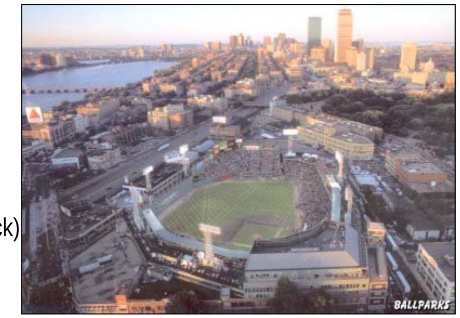
- Questec company
  - Ex-Wall Street (Ed Plumacher) and an ex-Yankee pitcher (Ron Klimkowski) bought Northrup Grumman tracking technology
  - Plan 1 – Sell system to teams
  - Plan 2 – Sell data to broadcasters (Fox Sports)
  - Plan 3 – Give data to broadcasters, sell advertisements to make money
- Questec system problems
  - Requires extensive setup and calibration (>2 hours using survey equipment)
  - Requires operator queing of each pitch
  - Used old Matrox board, and Questec bought up every board they could find
  - Could only field a few systems in select ballparks

A Little History (how we got involved)

- Had already demonstrated cool video processing and tracking technology in sports world
  - Tracked wind (cat's paws) to help win 1992 America's Cup for Bill Koch
- Serendipity
  - We saw Fox Broadcast for MLB playoffs in 2001
  - Approached Questec, and convinced them that we could build a new and better system
  - They gave us three months to field a system for Fenway Park and they would do a bake-off between systems
  - When they saw how easy it was to setup and use and its accuracy, they ditched their system and the rest is history: Fox Sportsnet, Professional Tennis Tour, MLB pitch tracking system (replaced in 2009 by Zone Evaluation system when Questec failed as a business concern)

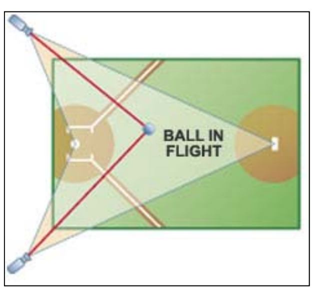
Problem Space

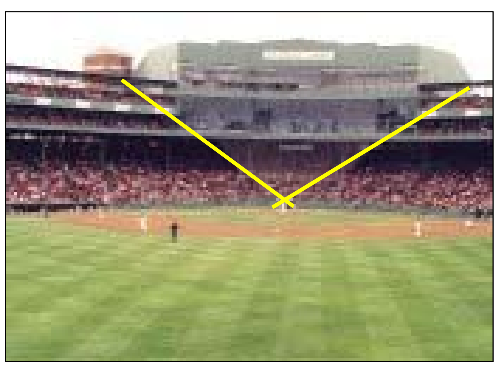
- Ball
  - Known size, color
  - Background, variable (sun shadow, debris, rain, snow, birds, players)
- Venue
  - MLB Ballparks
- Equipment
  - Inexpensive cameras
  - PCs
  - Digitizing board
  - Analog video mixer
  - Timebase (written to sound track)



Camera Placement

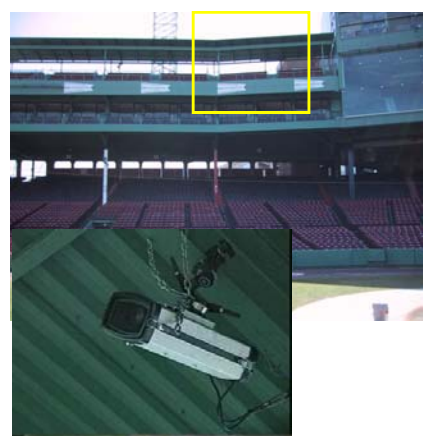
- Two cameras to solve for ball (x,y,z,t)
- High placement to see the pitching corridor





Camera Placements

- Attached to ceiling girders



Field Cameras

- Cameras to collect lefty/righty batter strike zone views

Center Field Broadcast Camera

- Broadcast feed to provide movie snippet of pitch for umpire review

Overall Approach

- Relies on fast ball extraction
- Calibrated camera model, in-game updates
- Track filter suitable for ball trajectories

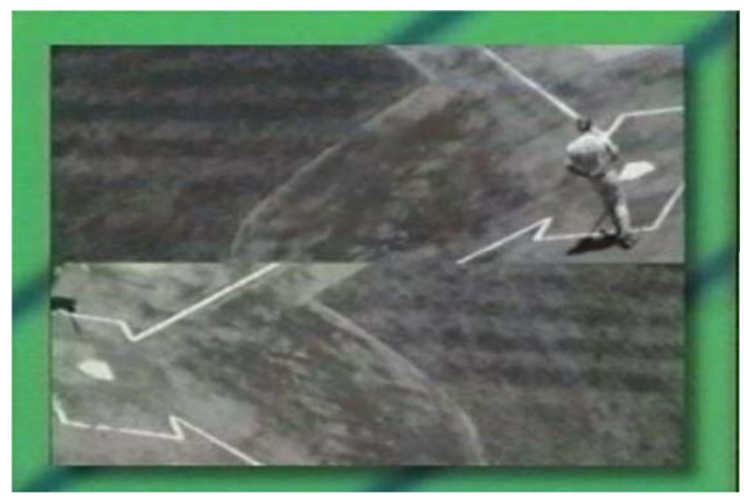
• frame difference
• ball morphology
• clutter rejection

• calibration procedure
• field lines tracking

• smoothing filter

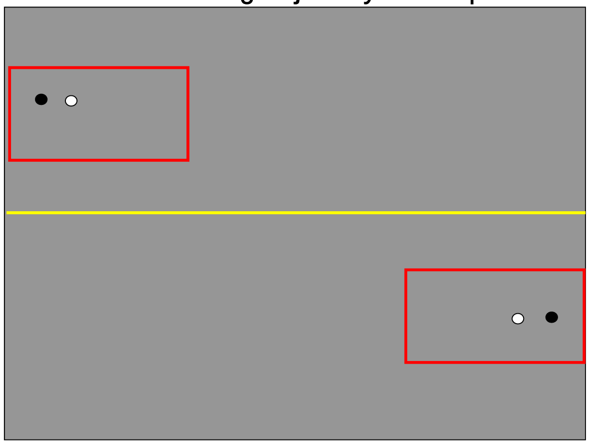
Simultaneous Camera Feeds

- Video Mixer allows single frame-grabber card, cameras externally sync'ed
- Pitch appears simultaneously in both images (L to R) (R to L)



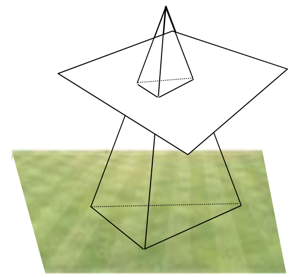
Ball Extraction

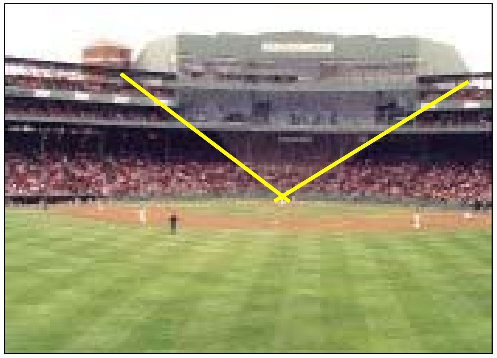
- Frame differencing
- Focused processing for valid pitch
- Two valid detections along trajectory before pitch declared



Calibration Approach

- Each camera done independently
- Use calibration pattern placed on field
- Photogrammetry solution: Church's method of space resection
- Ideal camera model
- Known focal length

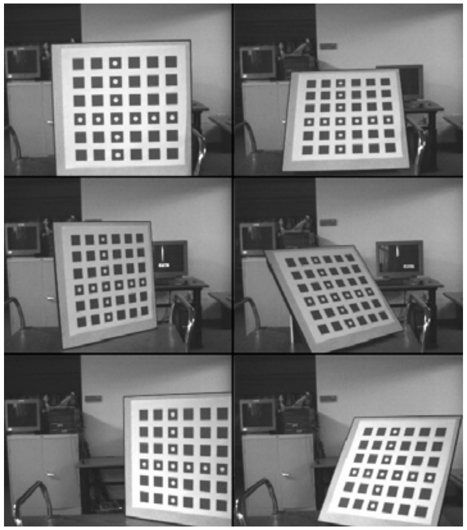




- *Each pixel (n,m,t) yields a line-of-bearing using camera models*
- *Ball position (x,y,z,t) is at the "intersection" of LOBs*

Zhang's method for Camera Intrisic and Extrinsic Parameter Estimation

- Zhang's method using multiple views of a calibrated array moving through the field of view
- Would solve for Extrinsic (6 DOF for camera position and pointing) and Intrinsic (Focal length and distortion)

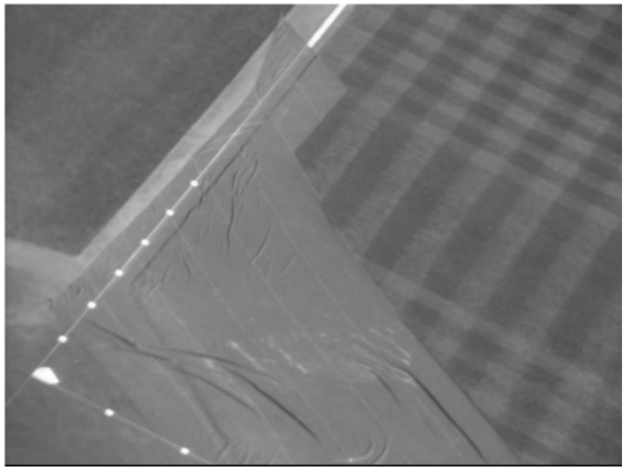


Calibration Targets for Extrinsic Camera Parameter Modeling

- Field disks plus ball array

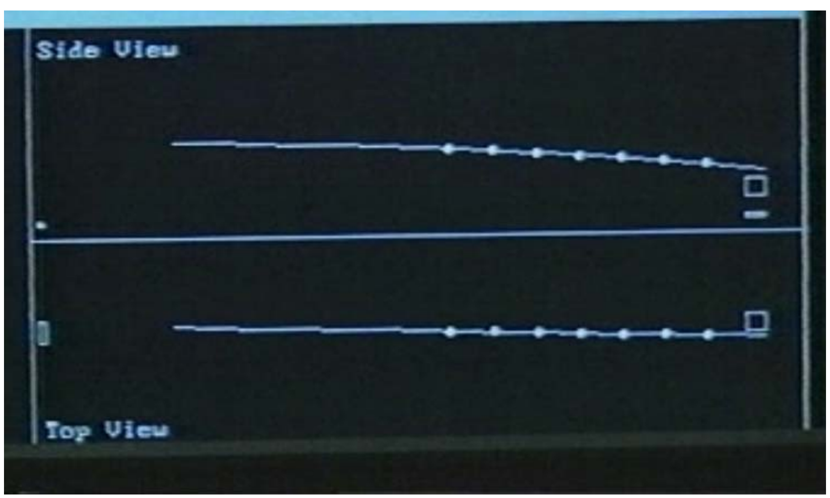
Calibration Targets for Extrinsic Camera Parameter Modeling

- Linear arrays



Tracking Pitches

Tracking Pitches



Practical Issues

- Movements of cameras
  - Wind vibration, fan stomping
  - Slow heating of steel girders
- Changing light conditions (stadium shadow)
- Snow, rain
- Birds and other intervening objects (thrown by fans)

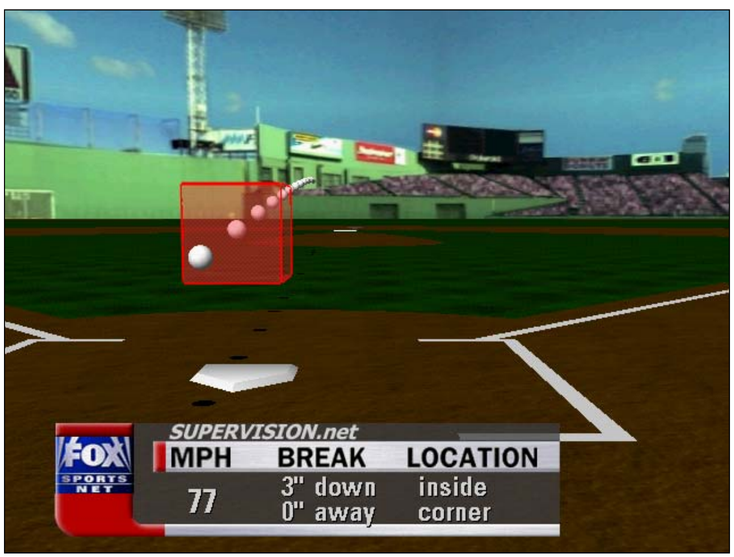
Trajectory Smoothing

- Smoothing done after all 4-D samples extracted
- Piecewise polynomial smoothing (7 points)
  - Pedro's fastball could have as few as 7 samples
  - Wakefield's knuckleball could have as many as 11
- Last polynomial used to extrapolate over the plate
- Measured ball locations to estimates of ball locations at back plane (apex of home plate) confirmed 1-sigma accuracy

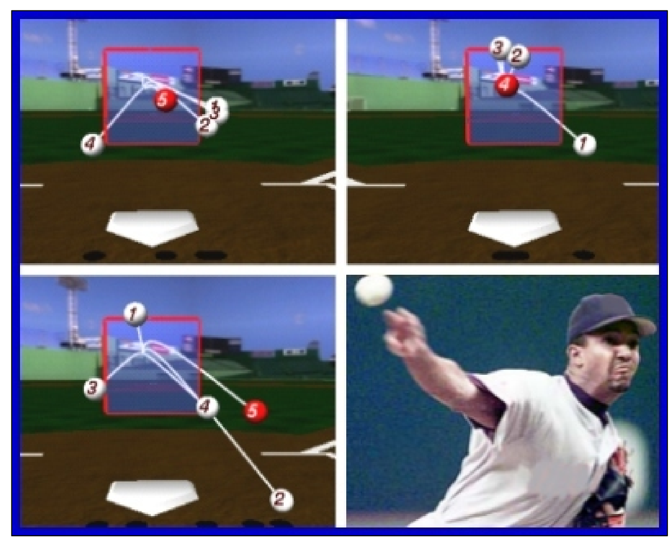
Ball Position Accuracy

- Broadcast system: 1.5"
  - Wider field of view, cheap surveillance cameras, trajectories from mound to plate
- Umpire Information System: 0.5"
  - Emphasizing area near plate, higher resolution cameras*
  - Not worrying about accurate trajectories all the way back to the mound

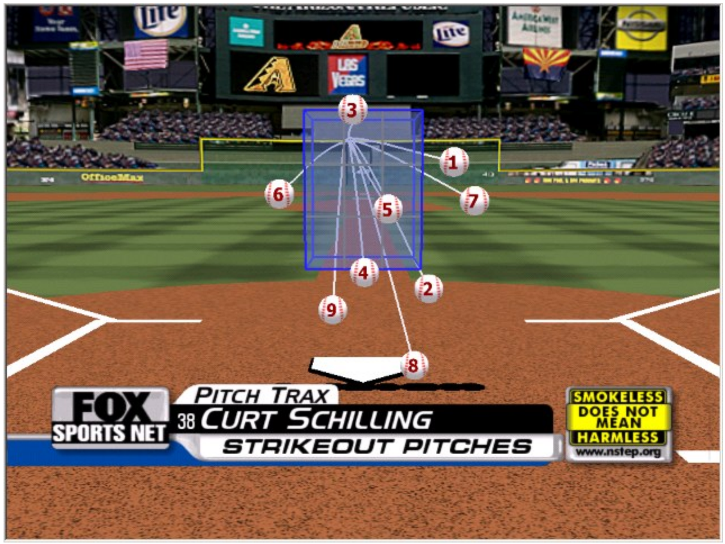
Fox Broadcast Samples



Fox Broadcast Samples



Fox Broadcast Samples



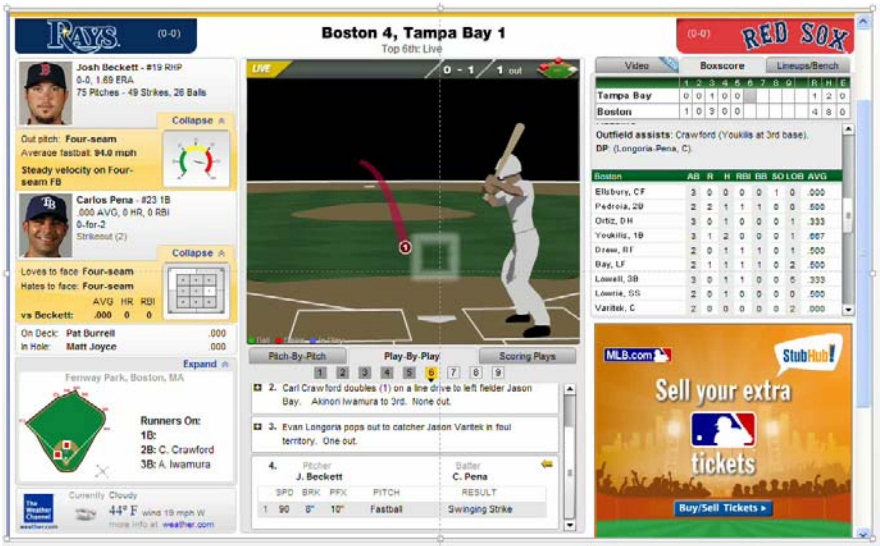
Vertical Strike Zone Determination

Umpire Information System

Umpire Information System

Called Ball	N	watch	batter	view
Called Ball	Y	watch	batter	view
Called Strike	Y	watch	batter	view
Called Ball	Y	watch	batter	view
Called Ball	Y	watch	batter	view
Called Strike	N	watch	batter	view
Called Ball	Y	watch	batter	view
Called Ball	Y	watch	batter	view
Called Ball	Y	watch	batter	view
Called Ball	Y	watch	batter	view
Called Ball	Y	watch	batter	view

Game Day on MLB.com 2007



All-Star Game Day on MLB.com 2018