# Overview

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

## Basic Image Processing Tools

- Lighting Considerations
- Thresholding
- Morphological Filtering
  - Basic operations
  - Size sorting
  - Skeletonization
- 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 $\mu_1$ and $\mu_2$ 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*

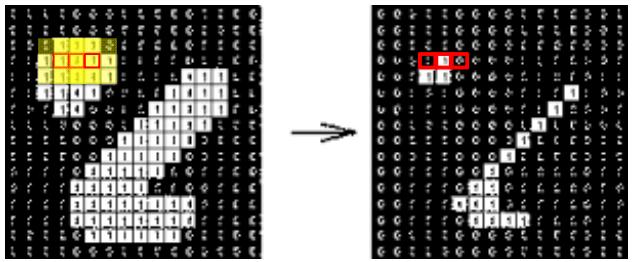
## Binary Morphology

- 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

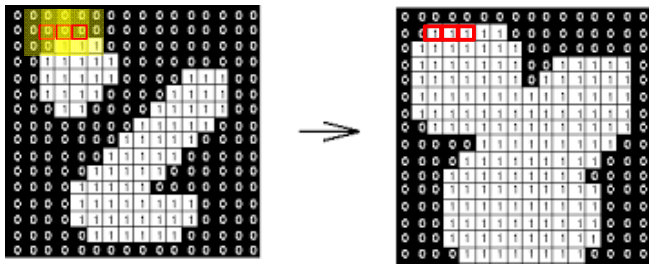
- Erosion

3x3 SE



- Dilation

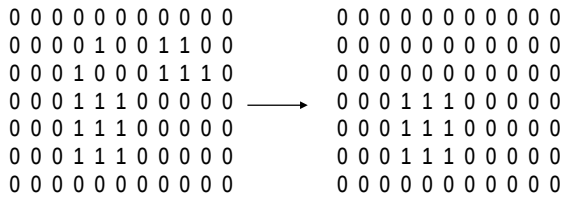
3x3 SE



## Examples of Opening and Closing

- Opening

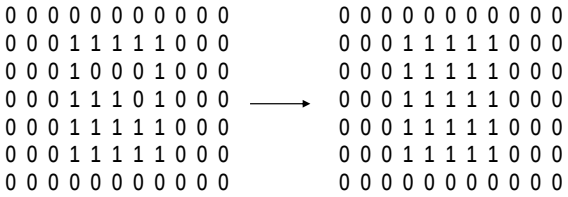
  3x3 SE




*Removes noise*

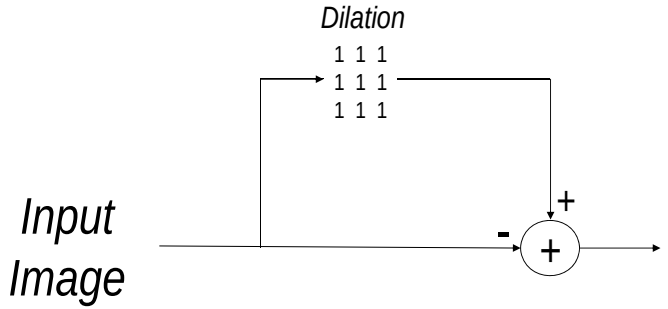
- Closing

  3x3 SE

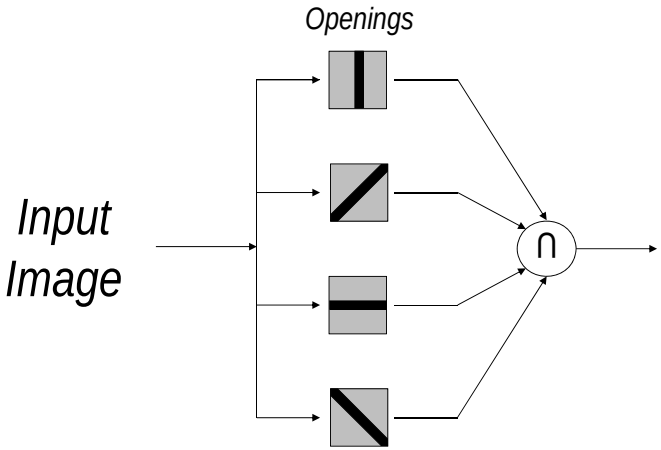



*Fills in holes*

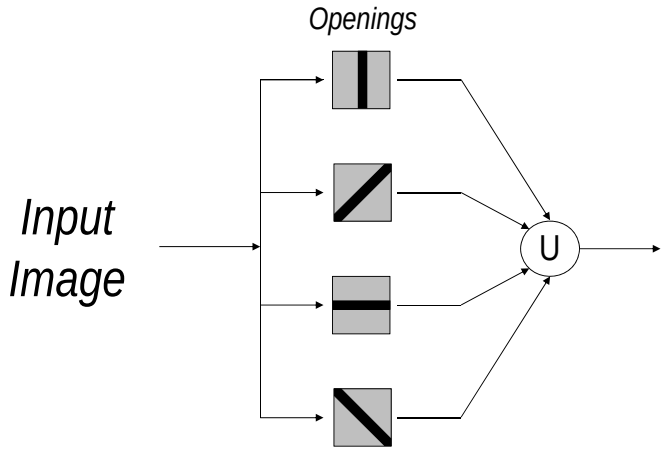
## Binary Edge Detection




## 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

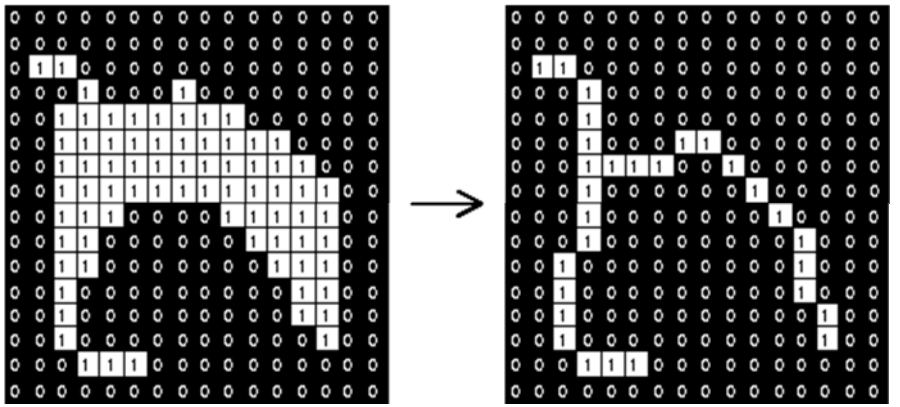
- At each iteration, the image is first thinned by the left hand structuring element, and then by the right hand one, and then with the remaining six *90°* rotations of the two elements. The process is repeated in cyclic fashion until none of the thinnings produces any further change.

| | | |
|---|---|---|
| 0 | 0 | 0 |
| | 1 | |
| 1 | 1 | 1 |

| | | |
|---|---|---|
| | 0 | 0 |
| 1 | 1 | 0 |
| | 1 | |

*Skeletonization Structuring Elements*

## Skeletonization Example

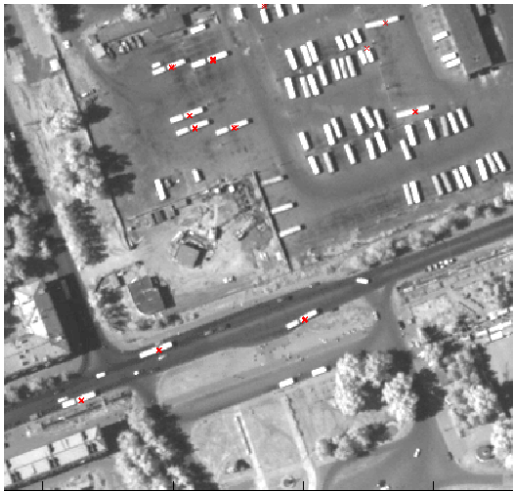


## Correlation for Object Detection

- 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 position
  - 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

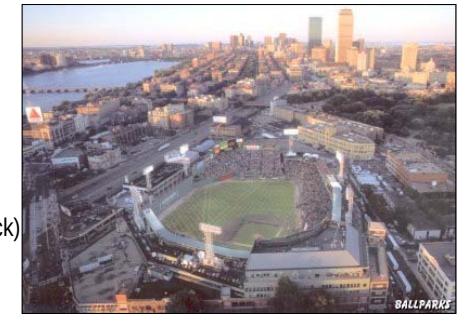
- Questec company
  - Ex-Wall Street (Ed Plumacher) and an ex-Yankee pitcher (Ron Klimkowski) bought Northrup Grumman tracking technology
  - Plan 1 – Sell system to teams
  - Plan 2 – Sell data to broadcasters (Fox Sports)
  - Plan 3 – Give data to broadcasters, sell advertisements to make money
- Questec 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)

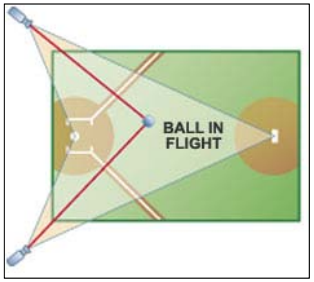
# Problem Space

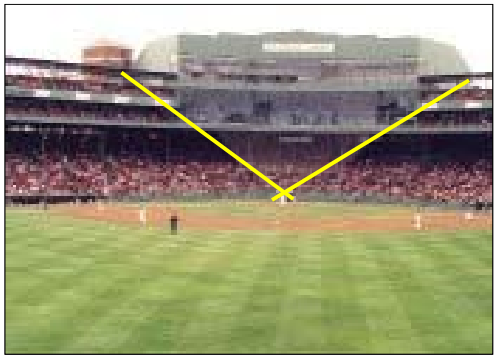
- Ball
  - Known size, color
  - Background, variable (sun shadow, debris, rain, snow, birds, players)
- Venue
  - MLB Ballparks
- Equipment
  - Inexpensive cameras
  - PCs
  - Digitizing board
  - Analog video mixer
  - Timebase (written to sound track)




# Camera Placement

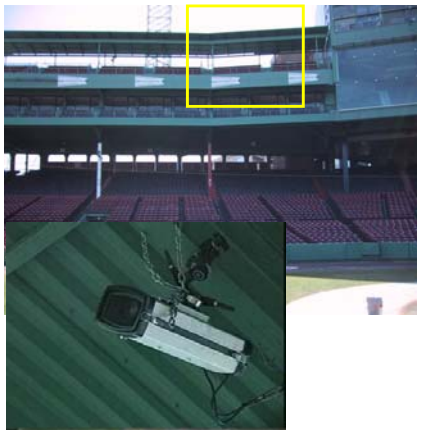
- Two cameras to solve for ball (x,y,z,t )
- High placement to see the pitching corridor



# 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**

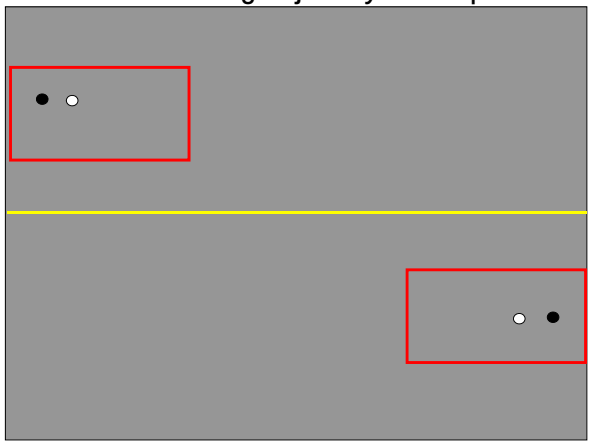
- **smoothing filter**

# 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)

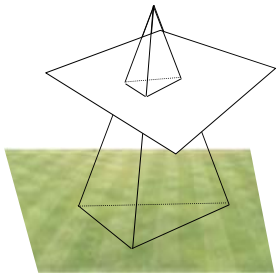
# Ball Extraction

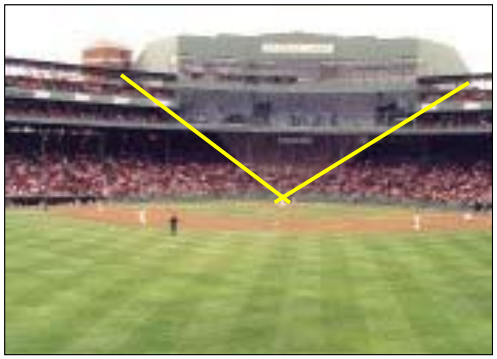
- Frame differencing
- Focused processing for valid pitch
- Two valid detections along trajectory before pitch declared



## 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



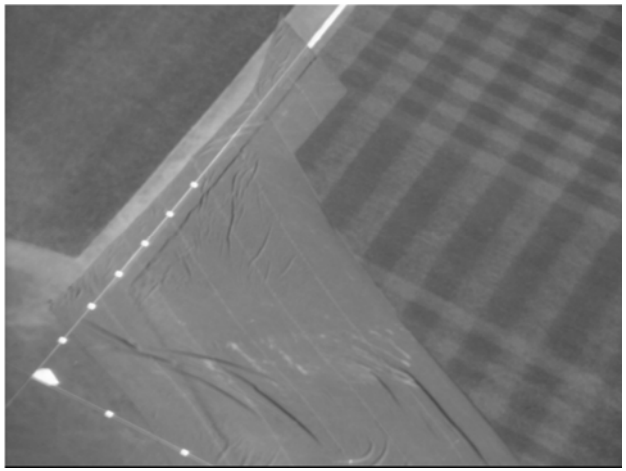


## Calibration Targets

- Field disks plus ball array

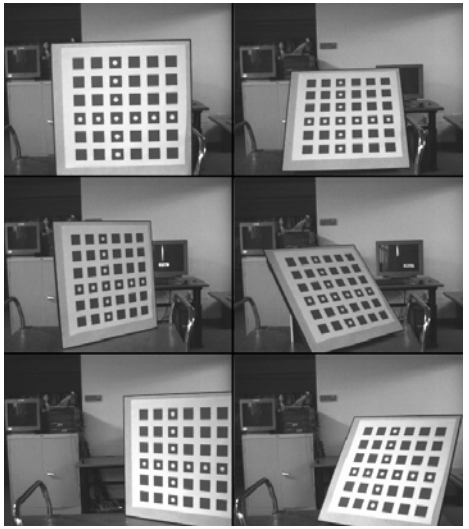
## Calibration Targets

- Linear arrays



## Much Better Calibration Method

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



## 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)

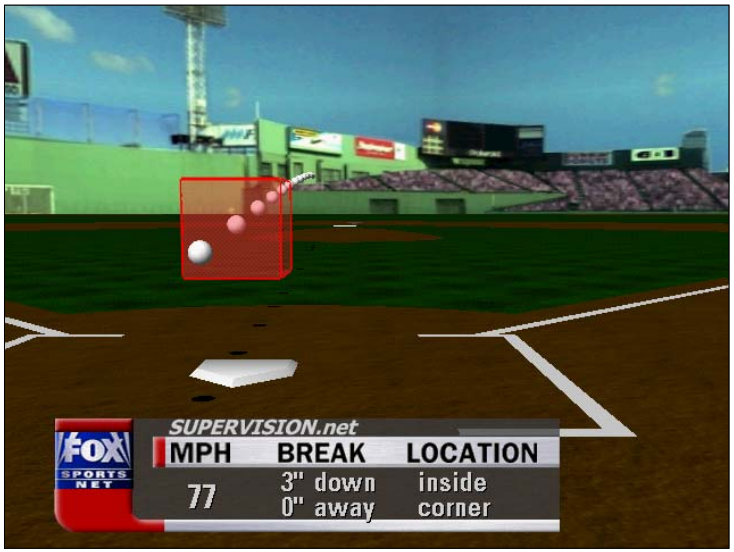
## Trajectory Smoothing

- 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

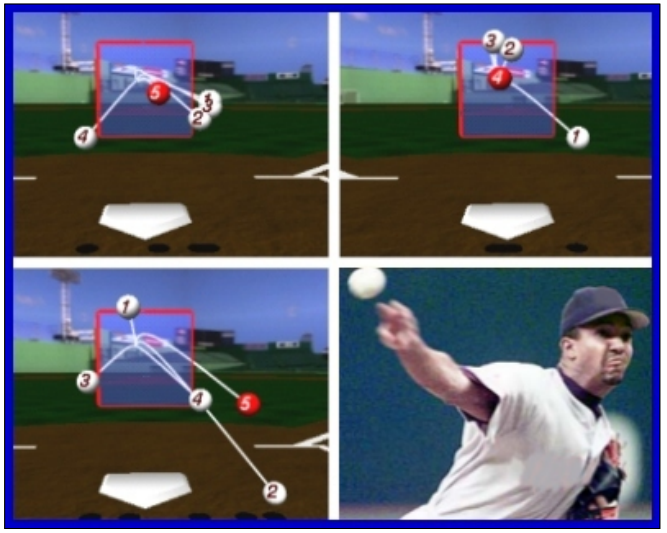
## Accuracy

- 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 trajectories all the way back to the mound

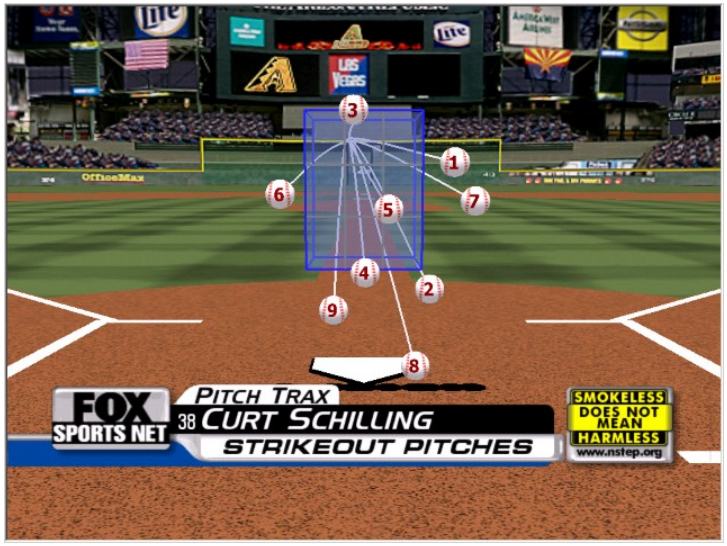
## Fox Broadcast Samples




## Fox Broadcast Samples



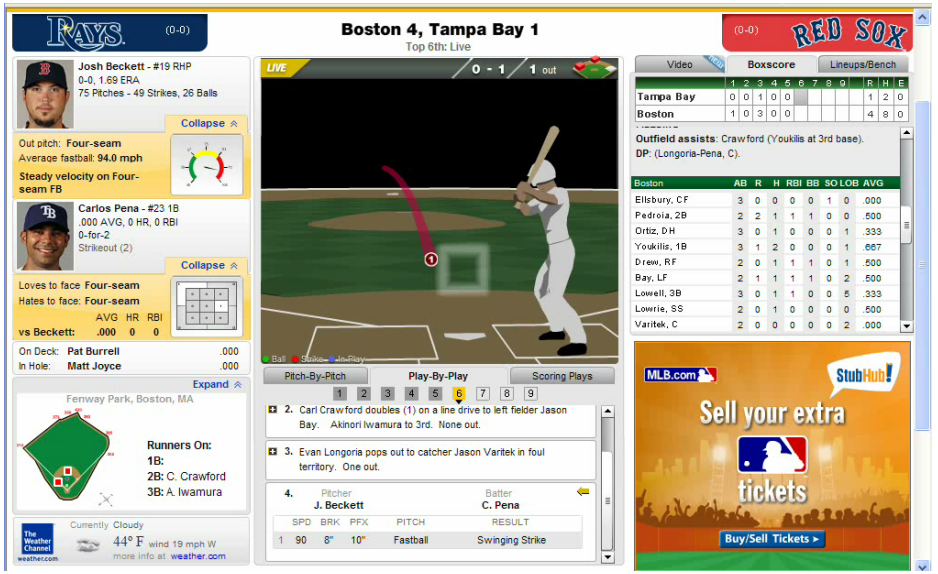
## Fox Broadcast Samples




## Vertical Strike Zone Determination

# Umpire Information System

# Game Day on MLB.com 2007




# MLB.com App on Ipad 2015