Single Image 3D Reconstruction of Ball Motion and Spin From Motion Blur

An Experiment in Motion from Blur

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Objective

From a single image, reconstruct:
- Ball 3D position
- 3D velocity
- spin axis
- angular speed

We analyze motion blur affecting the ball image exploiting known scene geometry.
Motivations

- Multi-frame approaches often tricky due to:
  - motion blur/noise tradeoff (exp. indoors)
  - too few/too many similar features on ball surface
  - frame rate too low for spin reconstruction
  - resolution too low for 3D localization

- Our approach:
  - high resolution (one 8+ MPixel DSLR photo, triggered shutter).
  - works with any texture on ball surface
  - exploits intra-frame information
Requirements

- Known exposure time
- Ball appears (slightly) blurred
- Ball surface color not homogeneous
Assumptions

- Exact perspective
- Spherical ball
- During exposure time:
  - Ball trajectory locally straight
  - Ball apparent translation less than \(1/5\) of apparent radius
  - Spin angle 1 to 10 degrees
- Usually met in practice if appropriate exposure time is used
Shan, Qi Xiong, Wei Jia, Jiaya: *Rotational Motion Deblurring of a Rigid Object from a Single Image*

- Concerned with deblurring
- Considers a simpler, 2D object geometry
- Rotational-only motion
- Uses alpha map as transparency cues
Ball trajectory reconstruction from a single long-exposure image (CVBASE 2006)

- Exploits single high resolution image as well
- Longer exposure
- No spin recovery
3D position and 3D velocity estimation (ICIAP 2007)

- Similar requirements
- Restrictive requirements on ball and background appearance (uniform color)
- No spin recovery
Motion blur model

The blurred image is obtained as the temporal average of many still images over the exposure time.

- Both translation and spin affect the ball appearance;
- Only translation affects the ball’s apparent transparency (alpha)
Alpha matting allows translation and spin separation

Alpha matting algorithms provide:

- An alpha map, representing the ball translation. Alpha at a pixel $p$ represent the fraction of the exposure time during which the ball image overlapped $p$ [Caglioti, Giusti BMVC2007]
- A foreground map, showing the ball surface without background
Local estimation of blur directions

- We locally estimate the direction of blur on the ball surface (from foreground map)
- Minimum derivatives algorithm
  - Reliable direction estimates
  - Unreliable extent estimates due to nonrectilinear blurring paths
- NO INFORMATION ON ORIENTATION!
Simplified case: no apparent translation

Sharp ball contours

⇒ ball position from ellipse fitting and calibrated camera
Simplified case (2) -- Spin axis recovery

- Backproject blur directions on 3D surface
- find 3D directions of ball surface displacement
- Two such directions identify spin axis (perpendicular to both)
Simplified case (3) -- Robustness in spin axis recovery

- We have many local blur directions
- Corresponding 3D directions should be coplanar
- Robust fitting of a plane with iterative outlier removal. Iteratively repeat:
  - Least squares fitting of plane to 3D directions using SVD
  - Outlier identification and removal using fixed threshold

Inliers (yellow)
Simplified case (4) -- spin angle recovery

- Spin angle during exposure is robustly recovered as median of angles:
  - backprojection of local blur lengths on ball surface (excluding outliers)
- Spin angular speed immediately follows
The spin+translation case is much more difficult
General case (2): position and velocity estimation

- First step: find ball position and velocity using known technique on alpha map only [ICIAP2007]
- Find apparent motion direction (radon-like transform)
- Analyze parallel profiles
- Find gradient discontinuities along profiles → contours of the ball at beginning and end of the exposure
- Fit initial and final ellipses
- 3D localization → position and velocity
General case (3): geometry of spin recovery

Must backproject blurring path endpoints on initial/final spheres!
General case (4): orientation problem

- No easy way to determine which sphere each endpoint must be backprojected to.

  → Heuristics:
  - smooth vectorial field
  - consistent directions if velocity dominates spin

  Voting or RANSAC-like approaches possible
Experimental results

Remarkable accuracy on the spin-only case, both in simulated and real images

Specularities and bumps in ball surfaces are handled well although not explicitly modeled
Experimental Results (2) – Quantitative data

Mean relative error (percent) in spin angular speed estimation on synthetic images

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Spin angle (deg) | Noise
Experimental Results (3) – Real images
Experimental Results (4) – Real images
Experimental Results (5) – Real images
Experimental Results (6) – Real images
Experimental Results (7) – General case

- Correct: ball was rolling on the table:
- Displacements on contact point are null
- Axis is parallel to the table
The general case is not at all robust and still problematic:
- Heuristics for blur orientations often fail
- Current technique needs blur extents, which are not reliable due to curvilinear blurring paths

We are developing a voting-based approach which does not require blur extents

Alternative techniques can be used instead of minimum derivatives [Caglioti, Giusti PACV2007] with promising results, handling more difficult cases:
Conclusions

- A single high resolution photograph can sometimes be a viable approach for motion reconstruction
  - No need for solving the correspondence problem
- The known scene structure is an important prerequisite.
- We separate the problem into translation and spin recovery thanks to alpha matting
- The orientation of local blur estimates is unknown and poses important challenges