Physics-Based 3D Ball Trajectory Reconstruction from Monocular Soccer Video

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CVPR JUNE 3-7, 2026 DENVER COLORADO

Introduction

TL;DR: We benchmark seven ball motion models of increasing complexity for 3D ball trajectory reconstruction across multiple datasets with ∼6,000 trajectory segments. We publicly release two new soccer datasets with densely-labeled triangulated 3D ground truth, including **Legia-Piast, LP** with paired static and broadcast captures. We compare these models under both monocular and multi-view settings, and how performance shifts between static and broadcast capture.

Problem statement

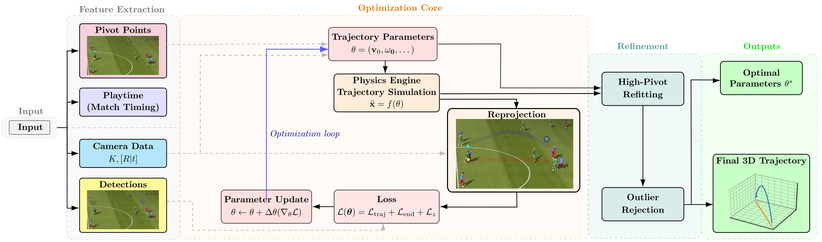
- Monocular 3D ball trajectory recovery is ill-posed due to depth ambiguity.
- Physics-based flight models (gravity, aerodynamic drag, Magnus effect) constrain the solution space, yet observation noise may render model parameters unrecoverable.
- Prior work commits to a single flight model and lacks a multi-view trajectory-level 3D evaluation protocol.
- Large-scale, densely-labeled 3D ball datasets remain scarce, restricting both method development and rigorous evaluation.

Main contributions

- **Physics model benchmark:** We implement and benchmark seven arc models, starting from basic parabola and adding drag, fitted gravity, lift/lateral spin decomposition, and full rigid-body MuJoCo simulation.
- **New datasets:** a full Ekstraklasa match recorded with six static 4K cameras and one broadcast camera (**LP**) and four short drill sequences recorded with eight static and one panoramic camera (**Stalowa Wola, SW**).
- **3D ground truth and annotations:** precisely triangulated 3D ground truth for LP and SW, with ball contact point and playtime annotations for all datasets.
- **Ranking reversal:** the best model under monocular reconstruction differs from the best under multi-view 3D fitting. Observation noise limits how complex a model we can recover from a single view.
- **mAP for 3D ball evaluation:** adaptation of object-detection mAP, combining coverage and precision across $\{0.25, 0.5, \ldots, 3.0\}$ m 3D distance thresholds.

Datasets

Dataset	Cameras	Resolution	Segments	Play %	Arc %	GT cov. %	3D fit %	Release
Legia-Piast	6s + 1d	4K / 1080p	2 818	55.8	24.8	96.9	91.6	Full
Stalowa Wola	8s + 1p	1080p / pano	518	73.5	33.0	99.0	94.2	Full
Ekstraklasa-Broadcast	1d	1080p / 720p	2 384	56.0	26.6	100.0	96.3	Results
ISSIA-3D	6s	1080p	113	65.1	32.4	63.2	59.9	Annotations



Each inter-pivot segment is fitted by minimizing the reprojection residual between a forward-simulated trajectory and observed detections; high pivots are corrected, adjacent segments re-fit, invalid ones rejected.

Physics models

Model	MuJoCo	Fitted Gravity	Drag	Magnus	Spin (ω_0)	#Params
parabola	–	–	–	–	–	6
kinetic	–	–	✓	–	–	7
fitg	–	✓	✓	–	–	8
angular	–	–	✓	✓	–	9
MuJoCo kinetic	✓	–	✓	–	–	6
MuJoCo angular	✓	–	✓	–	✓	9
MuJoCo ellipsoid	✓	–	✓	✓	✓	12

Monocular 3D reconstruction

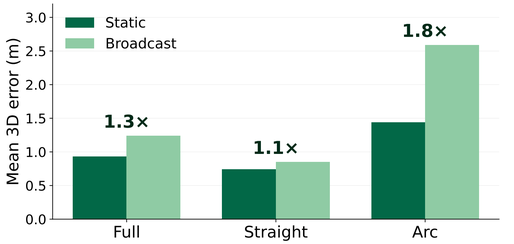
	LP-static		LP-broadcast		EB		SW		ISSIA-3D	
Model	mAP_{bal}	mAP_{arc}	mAP_{bal}	mAP_{arc}	mAP_{bal}	mAP_{arc}	mAP_{bal}	mAP_{arc}	mAP_{bal}	mAP_{arc}
parabola	.325	.274	.493	.330	.533	.357	.421	.351	.260	.159
kinetic	.332	.289	.508	.359	.532	.359	.414	.355	.253	.153
fitg	**.343**	**.307**	**.530**	**.397**	**.557**	**.412**	**.459**	**.371**	**.262**	**.163**
angular	.336	.296	.517	.377	.544	.383	.412	.353	.255	.157
MuJoCo kinetic	.329	.282	.496	.337	.525	.341	.422	.352	.260	.157
MuJoCo angular	.330	.283	.499	.341	.527	.345	.422	.351	.260	.158
MuJoCo ellipsoid	.324	.271	.494	.334	.522	.339	.437	.367	.261	.160

Multi-view 3D reconstruction (dm)

	LP		EB		SW		ISSIA-3D	
Model	Error	Arc Error	Error	Arc Error	Error	Arc Error	Error	Arc Error
parabola	3.16	4.68	3.80	5.88	1.92	7.24	5.90	3.64
kinetic	3.20	4.74	3.68	5.26	1.86	6.05	5.54	2.80
fitg	2.75	3.12	3.48	4.14	**1.78**	5.89	5.34	2.36
angular	**2.24**	**1.83**	**3.28**	**3.32**	1.83	**5.77**	**5.22**	**2.08**

Red / blue: predicted 3D trajectory and its pitch-plane projection. **Green / dark green**: oracle 3D ground truth and its pitch-plane projection. **Yellow**: segment endpoints.

Static vs broadcast



Paper · dataset · code