

Colour Particle Tracking Velocimetry: Resolving Spatial Identity Degeneracy in Dense Granular Flows Through Colour-Enriched Neighbourhood Descriptors

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Particle Tracking Velocimetry (PTV) is widely used for Lagrangian measurement in experimental soft matter research, yet it faces a fundamental limitation in dense granular systems. At high packing fractions, particles settle into locally regular packings where every particle's spatial neighbourhood becomes geometrically near-identical. PTV relies on spatial proximity for frame-to-frame linking and cannot distinguish between these degenerate neighbourhoods, producing identity switches and trajectory fragmentation even when detection is accurate. Granular matter also violates the continuity and small-displacement assumptions built into advanced fluid PTV codes, as violent collisions produce abrupt trajectory changes that defeat predictive linking designed for smooth flows. This spatial degeneracy (not merely occlusion or crowding) has been the principal barrier to complete particle-level measurement in dense granular flows, and the reason that foundational predictions (energy equipartition breakdown, convection cell structure, segregation dynamics) have remained validated only through simulation or indirect measurement.

We present Colour PTV (CPTV), which resolves this degeneracy by exploiting the fact that while spatial neighbourhoods in dense packings are geometrically identical, the colour arrangement within each neighbourhood is unique. We construct colour-enriched neighbourhood descriptors using CIE-LAB tracking kernels that encode both a particle's luminance structure and the chrominance of its surrounding neighbours via Gaussian-weighted colour blobs at each neighbour's relative position. These descriptors give each particle a distinctive tracking signature defined by who its neighbours are, not merely where they are. Normalised cross-correlation against the current frame yields high-confidence assignments, and a three-stage matching hierarchy (greedy confident, 2×2 block, Hungarian) resolves remaining ambiguities. GPU-accelerated multi-channel Hough circle detection with Bayesian refinement provides sub-pixel localisation.

We evaluated CPTV on a LAMMPS-simulated dense granular flow with 534 spheres in 3 distinct colours across 401 frames (1024×1024 pixels). CPTV achieves 99.33% F1 detection, 95.71% IDF1 identity preservation, 91.58% HOTA, and a fragmentation ratio of 1.04× at 1.3 s per frame on consumer GPU hardware. These results demonstrate that colour-topological neighbourhood descriptors enable complete Lagrangian tracking in dense particulate systems without requiring specialised illumination, deep-learning training data, or particle sparsity assumptions.