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Robust Real-Time Garment Fitting from 3D Point Clouds with Physics-Guided Uncertainty and Reliability Monitoring

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Abstract

Real-time garment fitting from 3D point clouds is a fundamental capability for telepresence, virtual try-on, and augmented reality. Yet, it remains difficult due to high-dimensional non-rigid deformation, frequent self-occlusion, and the need to maintain physically plausible cloth behavior under noisy measurements. Existing studies have improved geometric registration, learning-based reconstruction, or cloth simulation in isolation, but still lack a unified real-time framework that combines dense vertex-level tracking, uncertainty-aware sequential estimation, and physics-guided regularization for robust garment fitting under noisy and incomplete 3D observations. To address this gap, we propose Dense-Decoupled Adaptive Kalman Filtering (DD-AKF), an integrative sequential estimation framework that tracks dense garment vertices in real time while explicitly propagating uncertainty. To make high-dimensional filtering tractable, DD-AKF employs a block-diagonal (decoupled) covariance approximation that reduces per-frame complexity to linear time in the number of vertices while retaining per-vertex uncertainty estimates. Physical plausibility is incorporated by introducing differentiable stretch, bending, and collision energies as soft constraints in a Gaussian-approximate (sequential MAP) update, enabling an adaptive trade-off between sensor fidelity and physics under degraded observations. We also compute an online reliability score based on innovation (residual) statistics to monitor tracking quality and trigger robustification in the presence of occlusion or sensor corruption. Experiments on FAUST, CLOTH3D, and real capture sequences show reduced temporal flicker and penetration compared with representative optimization-based, stochastic filtering, and learning-based baselines, while maintaining competitive geometric accuracy at interactive rates (30+FPS). These results support reliability-aware deployment in practical virtual try-on and AR garment-fitting pipelines using commodity 3D sensors.

Keywords: real-time garment fitting; 3D point cloud processing; cloth deformation modeling; physics-guided Kalman filtering; uncertainty-aware estimation; reliability monitoring

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1 Introduction

Real-time digitization of dynamic, clothed humans enables telepresence, virtual try-on, and augmented reality (AR) retail [1–3]. While parametric body models such as SMPL and GHUM are widely adopted [4–6], stable garment fitting from raw 3D point clouds remains difficult. Clothing exhibits high-dimensional non-rigid deformation, complex topology, and self-contact, and visually plausible motion must respect physical regularities such as limited stretch, bending resistance, and non-penetration [7–9].

In practical capture pipelines that use consumer depth cameras or LiDAR, garment tracking is further degraded by measurement noise, partial observations due to self-occlusion (e.g., crossed arms), and abrupt changes in the visible surface support [10, 11]. For interactive use, a fitting method should therefore (i) scale to dense garment states, (ii) remain robust when observations are missing or corrupted, and (iii) encourage physical plausibility without exceeding real-time budgets.

Existing approaches broadly follow two paradigms: optimization-based registration and learning-based inference. Classical non-rigid registration methods—such as Non-Rigid ICP [12] and Embedded Deformation [13]—can achieve good per-frame geometric alignment when correspondences are reliable [14]. However, solving a new optimization at each frame can lead to drift under occlusion and high-frequency jitter ("temporal flicker") under noisy measurements [15, 16]. Incorporating strong physical constraints (especially collision handling and self-contact) into per-frame optimization further increases computational cost, often beyond real-time budgets [17, 18]. Learning-based methods infer garment geometry from pose cues or sparse observations [19, 20]. They can produce visually plausible reconstructions on in-distribution data (e.g., DeepFashion3D [21], SNUG [22]), but they may degrade under domain shift in motion, material behavior, or garment topology [23–25]. Many learning pipelines also provide limited calibrated uncertainty at test time, which makes online failure detection and mitigation more difficult [26, 27].

Despite these advances, a clear gap remains for interactive applications: existing methods rarely provide dense, point-cloud-driven garment tracking that simultaneously (i) propagates per-vertex uncertainty for confidence-aware updates, (ii) incorporates physical feasibility within the sequential estimator, and (iii) offers an online reliability signal to detect and mitigate failures under occlusion and sensor noise.

To address this gap, this study aims to develop a real-time garment-fitting framework based on 3D point clouds that can robustly handle noisy and incomplete observations while maintaining physically plausible cloth behavior. We propose Dense-Decoupled Adaptive Kalman Filtering (DD-AKF). This sequential estimation approach combines scalable uncertainty propagation with physics-guided constraints and an innovation-based reliability signal for adaptive robustification.

At a high level, DD-AKF maintains a temporally coherent prior through sequential filtering, adapts measurement trust using per-vertex uncertainty, and uses differentiable cloth energies (stretch, bending, and collision) as soft physical regularizers when correspondence quality deteriorates. A lightweight reliability score derived from innovation statistics provides online diagnostics and guides robustification in the presence of occlusion or sensor corruption.

The main contributions are: (1) a dense per-vertex garment state-space formulation with a block-diagonal uncertainty representation to enable scalable real-time sequential estimation; (2) a physics-guided update that injects differentiable stretch, bending, and collision energies as soft constraints in a sequential MAP view; (3) an innovation-based reliability score used to adapt mea-