DLO-Splatting: Tracking Deformable Linear Objects Using 3D Gaussian Splatting

Holly Dinkel*[1], **Marcel Büsching***[2], Alberta Longhini[2], Brian Coltin[3], Trey Smith[3], Danica Kragic[2], Mårten Björkman[2], Timothy Bretl[1]

[1]University of Illinois Urbana-Champaign, [2]KTH Royal Institute of Technology, [3]NASA Ames Research Center

*Equal Contribution

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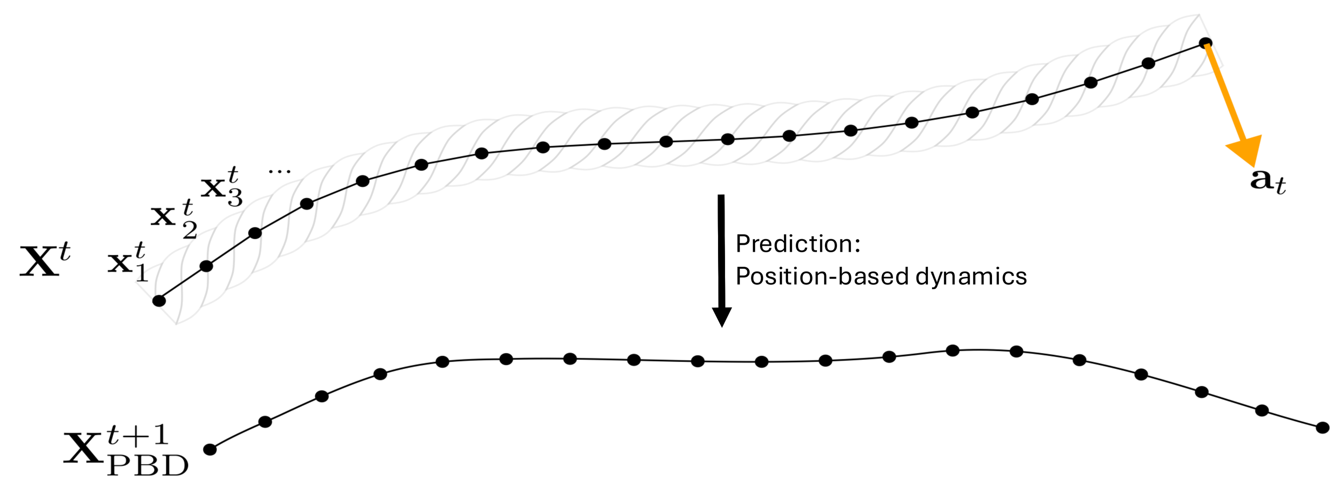
1 Introduction

The DLO-Splatting algorithm estimates the **3D shape of Deformable Linear Objects (DLOs)** from **multi-view RGB images** and gripper state information through **prediction-update filtering** [1]. The DLO-Splatting algorithm uses a **position-based dynamics model** to predict the object shape. Optimization with a **3D Gaussian Splatting**-based rendering loss iteratively renders and refines the prediction to align it with the visual observations in the update step. This method is promising for tracking the DLO topology during knot tying and other shape control tasks, particularly for tracking through total or out-of-view occlusion from one or more perspectives.



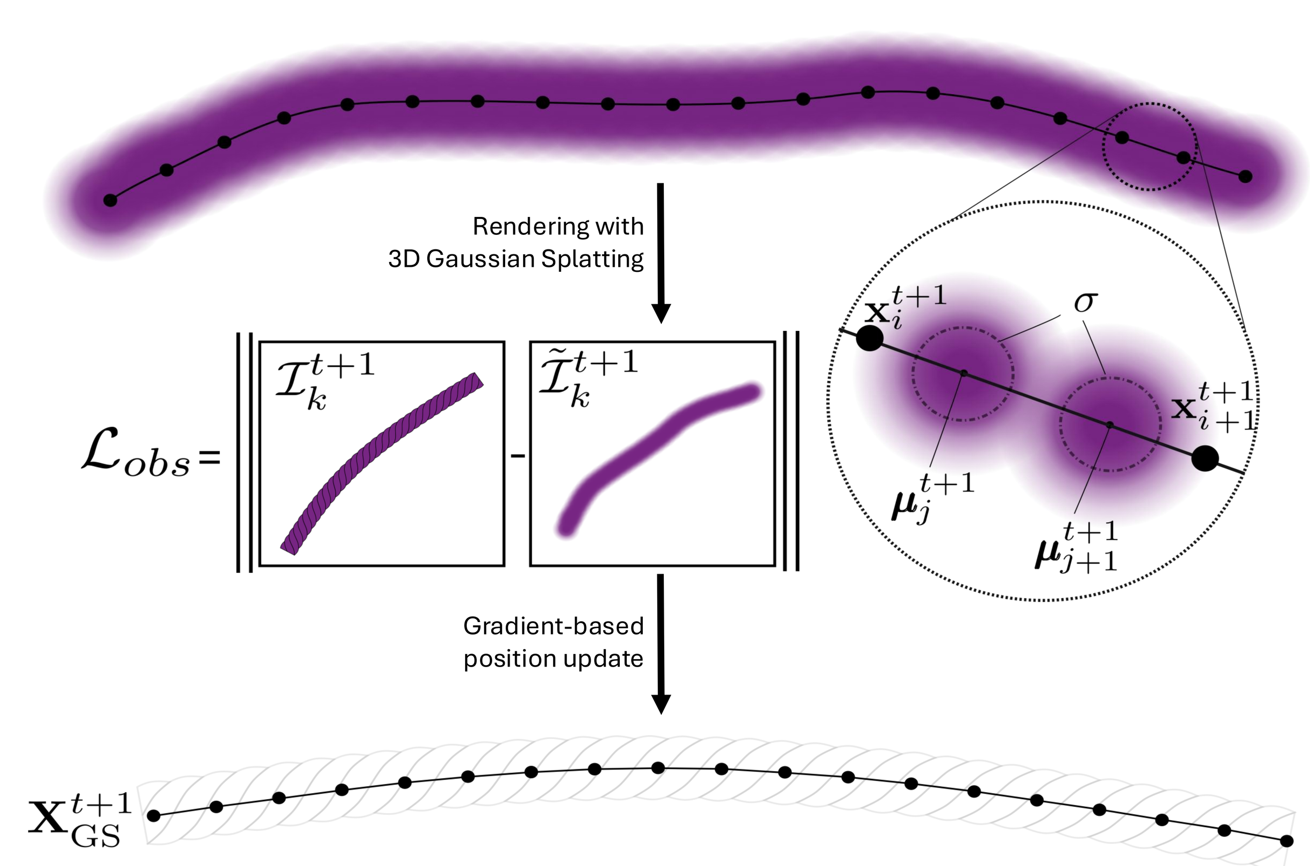
2 Prediction: PBD

- DLO-Splatting is initialized with TrackDLO [2], which uses occlusion-robust deformable one-dimensional object routing algorithm for initialization [3].
- Position-Based Dynamics (PBD) derived from physics first-principles are used to predict the next state of the rope given the current estimated state and a gripper position.
- The position of the rope is updated using Verlet velocity integration,

$$\mathbf{X}^{t+1} = \mathbf{X}^t + \left(\mathbf{X}^t - \mathbf{X}^{t-1}\right)\Delta t + \frac{1}{2}\mathbf{F}^t \Delta t^2,$$

  where the normal force, the force due to gravity, and the force of friction act on the DLO as $\mathbf{F}^t$.
- The grasped node is assumed to have the same position as the grasp center, and its position is propagated through the rope after integration to maintain lengths between adjacent nodes.
- After corrections, the predicted state of the rope is the concatenation of the position of each node,

$$\mathbf{X}_{\text{PBD}}^t = \left[\mathbf{x}_1^t, \cdots, \mathbf{x}_N^t\right]^\intercal.$$

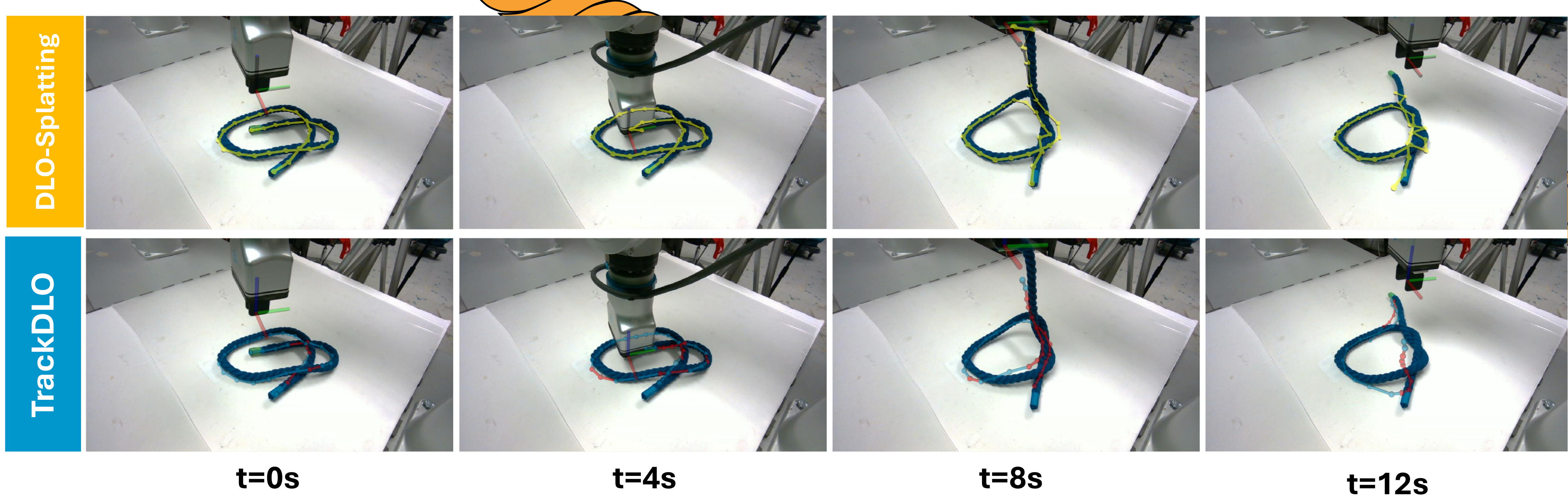


3 Update: 3DGS

- The DLO is represented as 3D Gaussian distributions, $G_j(\mu_j, \Sigma, \mathbf{c}_j, o_j)$, with mean (position), covariance, color, and opacity initialized at t=0.
- The mean is expressed relative to the nodes of the DLO, connecting their appearance and geometry.
- An image is synthesized by projecting the Gaussians onto the image plane and aggregating them via α-blending.
- The synthesized image is used to estimate a rendering loss to the observation, allowing for a gradient-based update of the node positions.
- The rendering loss, $\mathcal{L}_{obs}$, is used to iteratively update the node positions as

$$\hat{\mathbf{X}}^{t+1} = \mathbf{X}_{\text{GS}}^{t+1} = \mathbf{X}_{\text{PBD}}^{t+1} + \Delta\mathbf{X}^{t+1},$$

$$\text{where} \quad \Delta\mathbf{X}^{t+1} = \text{argmin}_{\Delta\mathbf{X}}\, \mathcal{L}_{\text{obs}}\left(\mathbf{X}_{\text{PBD}}^{t+1} + \Delta\mathbf{X}\right).$$



4 Results

- The DLO-Splatting algorithm is qualitatively compared to the TrackDLO algorithm on a knot-tying task passing one end of the DLO through a loop to introduce a new topological crossing.
- Both methods fail to correctly estimate the resulting topology for 8 seconds, although DLO-Splatting successfully tracks the grasped tip.

5 Conclusion

- The DLO-Splatting algorithm is well-suited for tracking through certain types of occlusion, such as when parts of the object move out of view of one or more cameras.
- A higher-fidelity physics simulator could enable better tracking in visually ambiguous scenarios when the topology of the DLO cannot be resolved from image data alone, for instance in dense knot configurations.

6 Limitations

- Limitations include difficulty modeling self-intersections, a slow update rate of 1 Hz, and reduced performance during occlusions.
- Future work could use a higher-fidelity simulator to model deformation or sample physics prediction at a high rate to improve resolution of physics constraints.

References

[1] Longhini et al., "Cloth-Splatting: 3D Cloth State Estimation from RGB Supervision," CoRL, 2024.
[2] Xiang et al., "TrackDLO: Tracking Deformable Linear Objects Under Occlusion with Motion Coherence," IEEE RA-L, 2023.
[3] Keipour et al., "Deformable One-Dimensional Object Detection for Routing and Manipulation," IEEE RA-L, 2022.

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