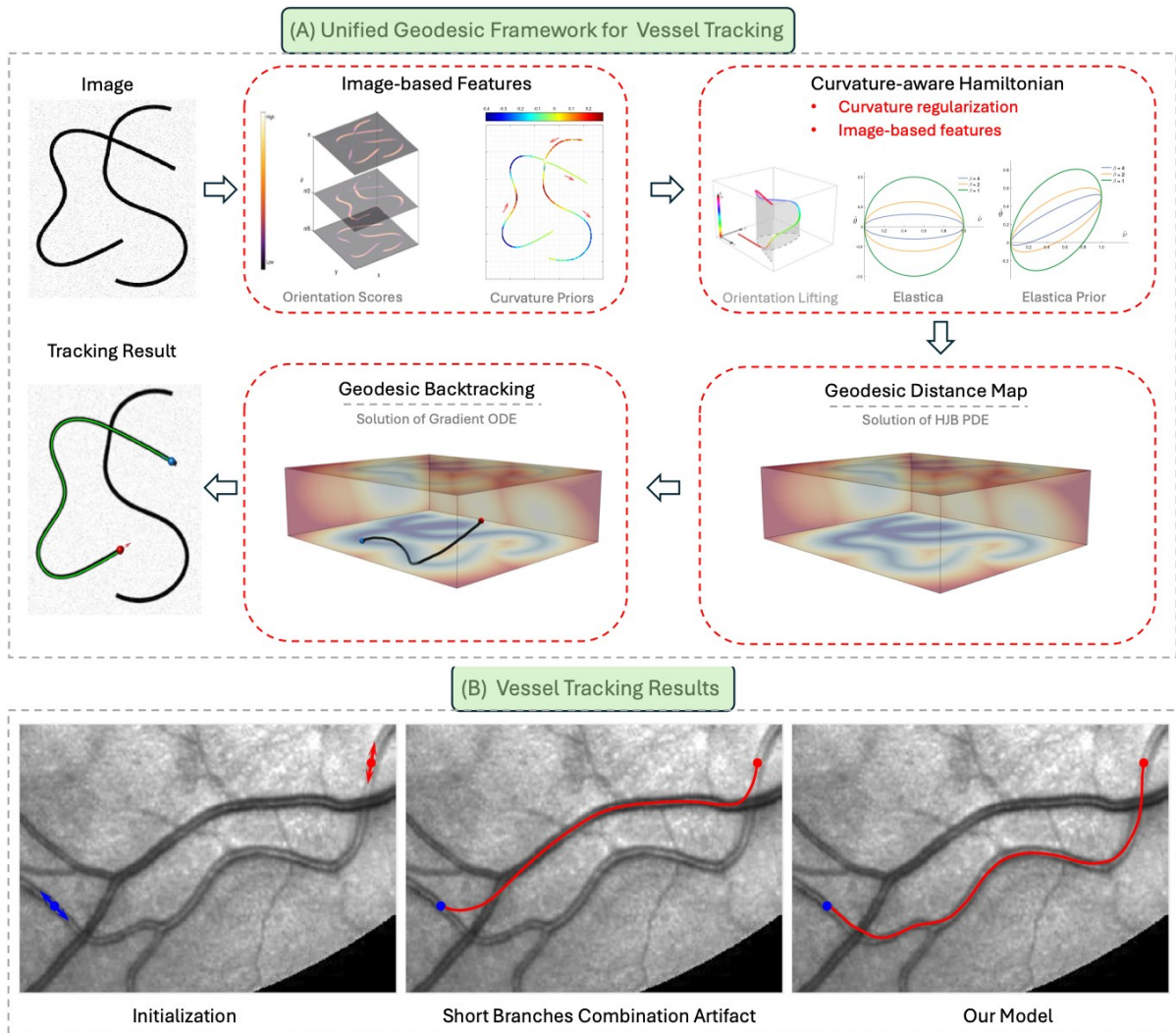


CURVATURE-PENALIZED GEODESIC MODELS FOR VASCULAR CENTERLINE EXTRACTION

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Our work on vessel segmentation has long been grounded in the computation of shortest paths, or geodesics, under image-based metrics. Extracting vessel centerlines is a fundamental task in biomedical image analysis, but remains challenging when vessels are tortuous, low-contrast, or closely intertwined. Traditional geodesic models often fail at crossings or merge nearby branches incorrectly. Curvature-penalized geodesic models provide a solution by treating the centerline as a globally optimal path that balances adherence to image features with smoothness and bending constraints. Our approach starts from the Finsler elastica model, which lifts the image into an orientation-lifted space, and defines a metric that encourages paths to follow both target image features and a natural bending pattern. In this framework, curvature is regarded as an intrinsic geometric prior rather than a postprocess procedure, allowing minimal paths to remain smooth and faithful even across challenging images. To better follow strongly curved vessels and handle complex junctions, we extend the elastica model with a curvature prior. Instead of simply limiting curvature, this model penalizes deviations from a reference curvature estimated from the data, guiding paths to bend naturally along vessel structures while avoiding shortcuts and incorrect branch combinations. We further expand the method from pointwise tracking to segment-wise graph connections, linking partial vessel segments with short curvature-regularized paths and then finding globally consistent centerlines. These computations occur in a three-dimensional space, leading to high computation costs. We use a fast iterative solver with parallel processing, allowing these high-order geodesics to be computed in a quasi real time manner. Together, these developments provide a reliable and interpretable framework for vessel centerline extraction.



Curvature-penalized geodesic framework for vessel centerline extraction. (A) Overview of the geodesic framework: raw images are first processed to compute image-based features, including orientation scores and curvature priors. These features are combined in a curvature-aware Hamiltonian defined in an orientation-lifted space, producing a geodesic distance map via the Hamilton–Jacobi–Bellman PDE. Centerlines are then recovered by geodesic backtracking. (B) Tracking results on a representative vascular image: initialization points are shown in blue and red. A baseline method exhibits shortcut and short-branch combination artifacts, while our model produces a smooth, accurate centerline that follows the vessel structure faithfully.