JIGGLE: An Active Sensing Framework for Boundary Parameter Estimation in Deformable Surgical Environments

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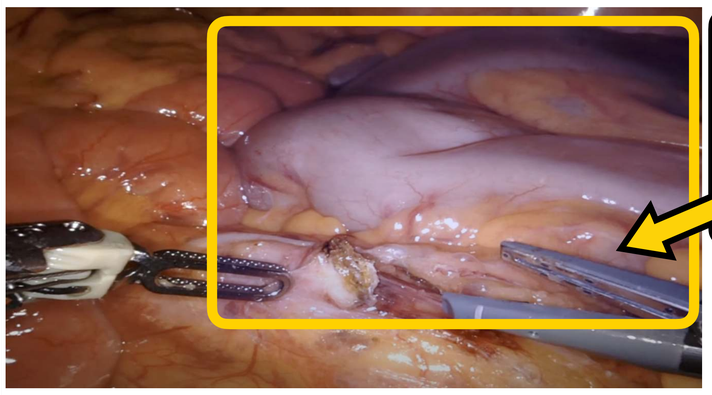
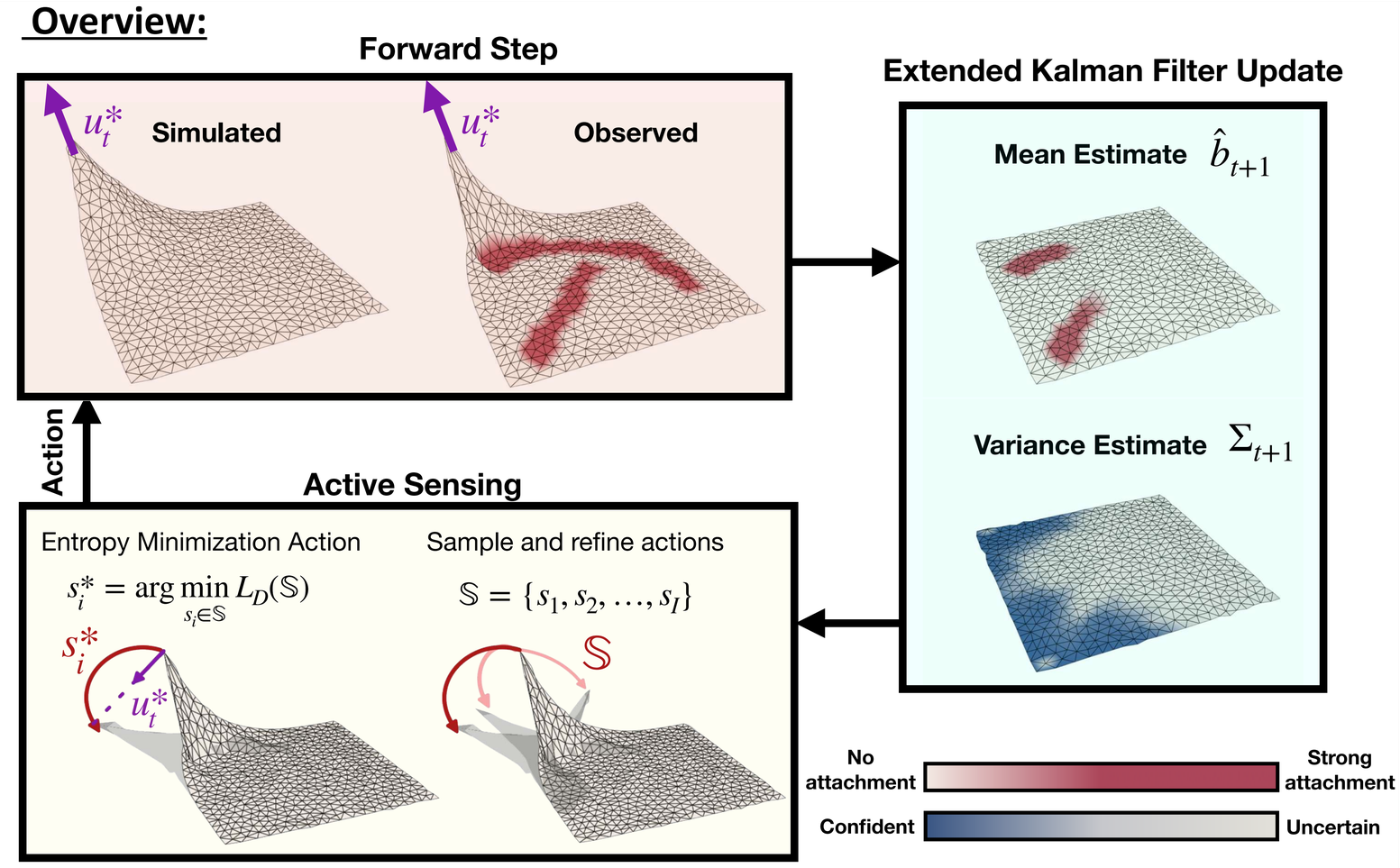
Motivation and Background:

Safe Surgical Autonomy



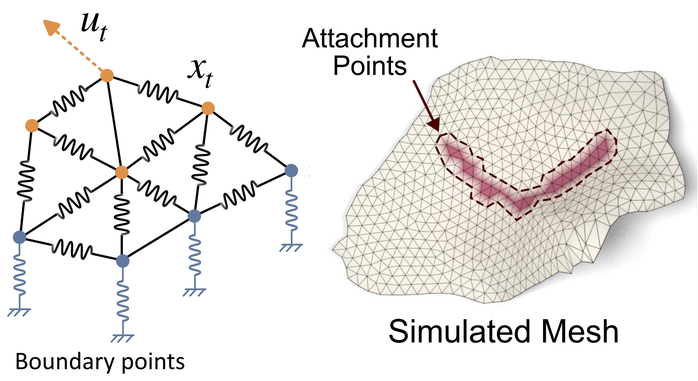
Overview:



Position Based Dynamics:

Differentiable Mass Spring Model: $f(x_t, u_t, b_t)$

- x_t : State
- u_t : Action
- b_t : Boundary attachment strength



Estimation: EKF

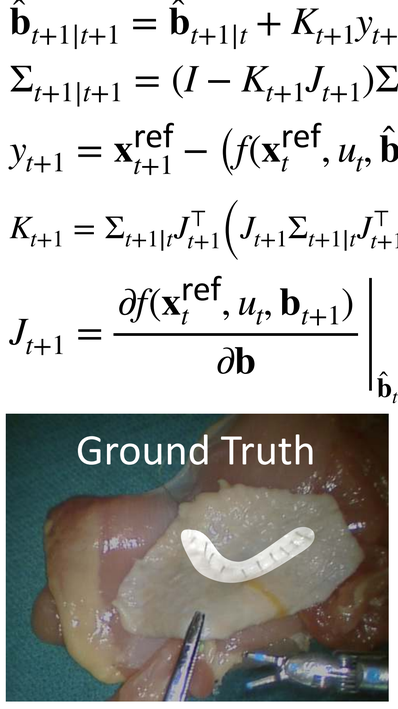
Prediction Step:

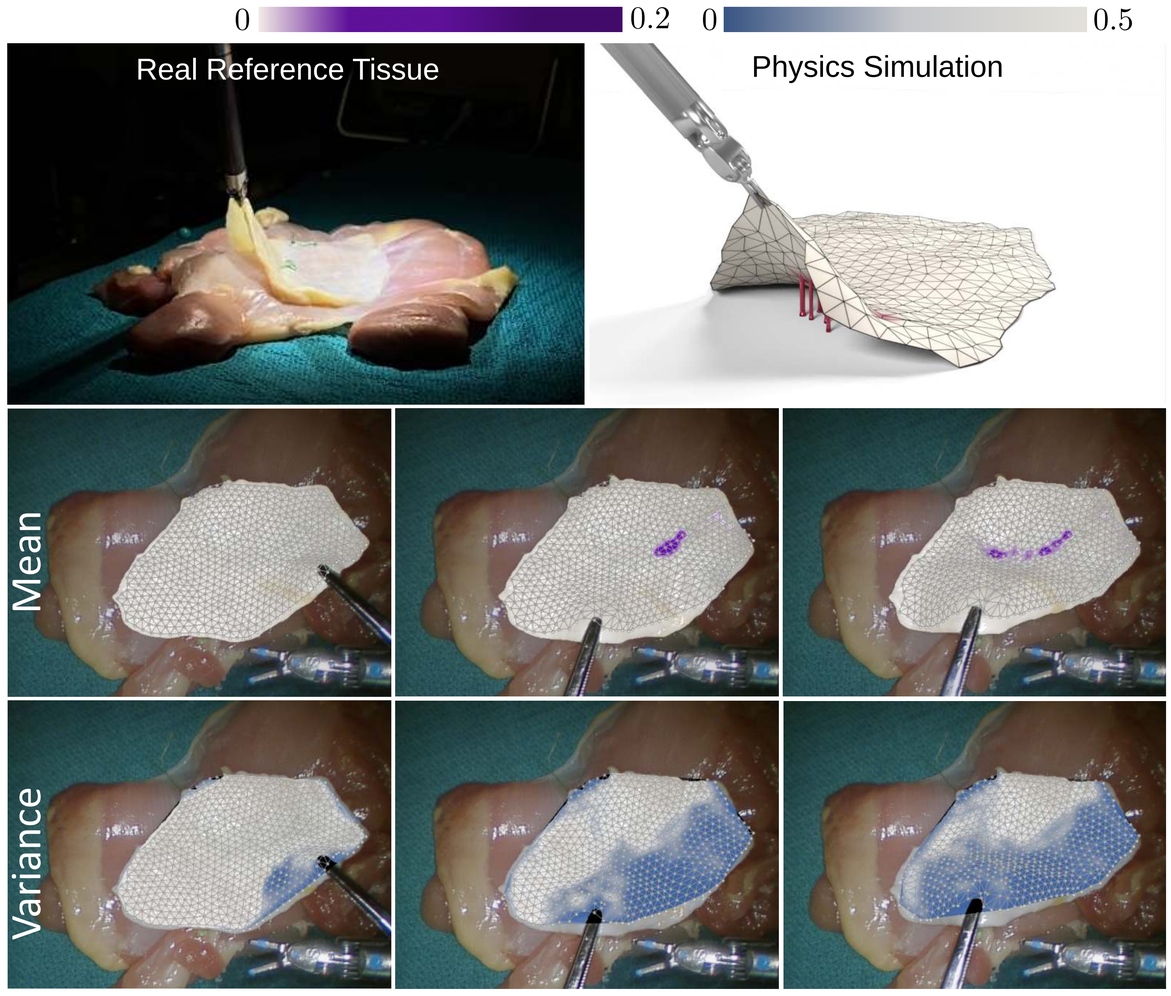
$$\hat{\mathbf{b}}_{t+1|t} = \hat{\mathbf{b}}_{t|t} + \delta \mathbf{b}_t$$
$$\Sigma_{t+1|t} = \Sigma_{t|t} + W_t$$

Update Step:

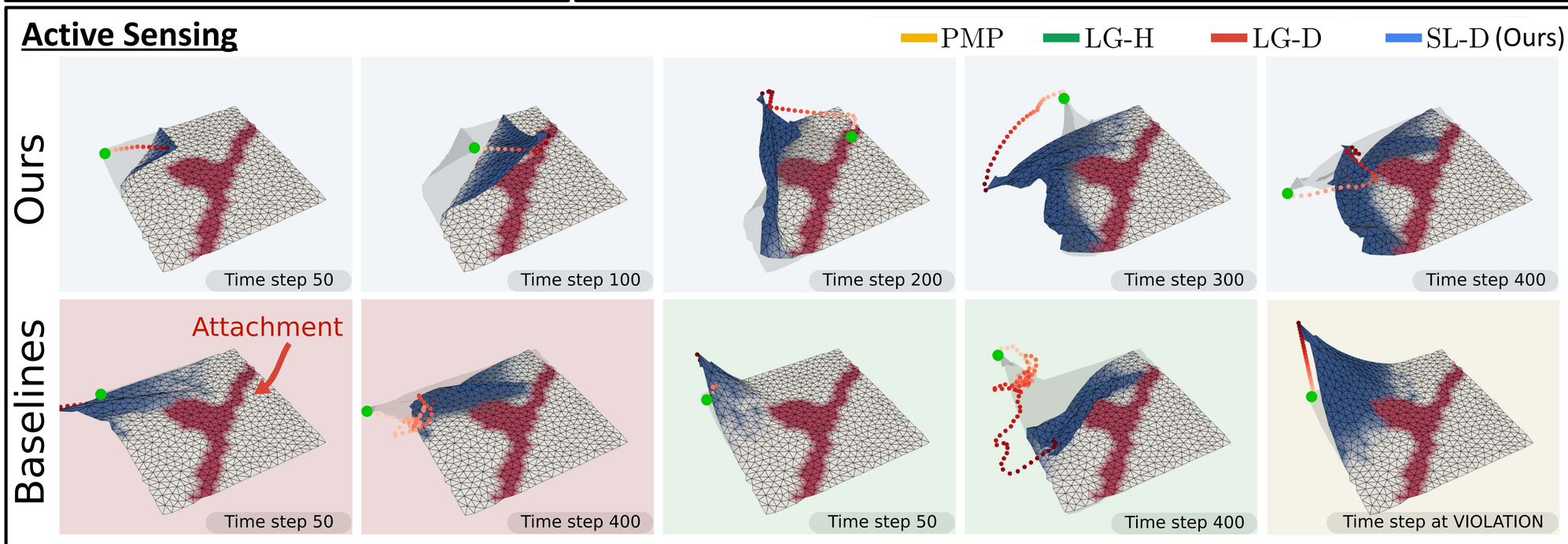
$$\hat{\mathbf{b}}_{t+1|t+1} = \hat{\mathbf{b}}_{t+1|t} + K_{t+1} y_{t+1}$$
$$\Sigma_{t+1|t+1} = (I - K_{t+1} J_{t+1}) \Sigma_{t+1|t}$$
$$y_{t+1} = \mathbf{x}_{t+1}^{\text{ref}} - \left(f(\mathbf{x}_t^{\text{ref}}, u_t, \hat{\mathbf{b}}_{t+1|t}) + v_t\right)$$
$$K_{t+1} = \Sigma_{t+1|t} J_{t+1}^\top \left(J_{t+1} \Sigma_{t+1|t} J_{t+1}^\top + I V_{t+1} I\right)^{-1}$$
$$J_{t+1} = \left.\frac{\partial f(\mathbf{x}_t^{\text{ref}}, u_t, \mathbf{b}_{t+1})}{\partial \mathbf{b}}\right|_{\hat{\mathbf{b}}_{t+1|t}}$$

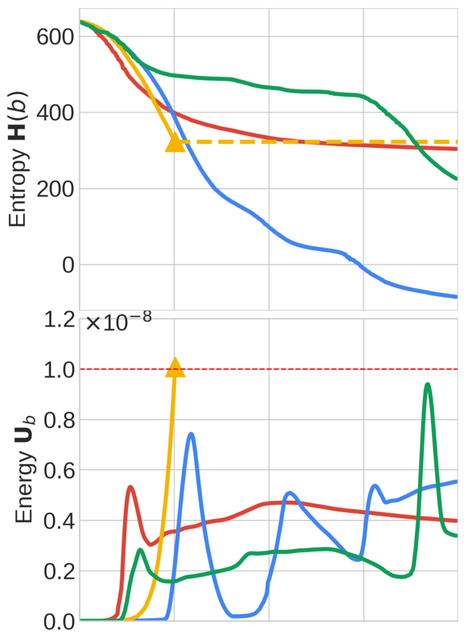
Leverage Differentiability of PBD!





Active Sensing



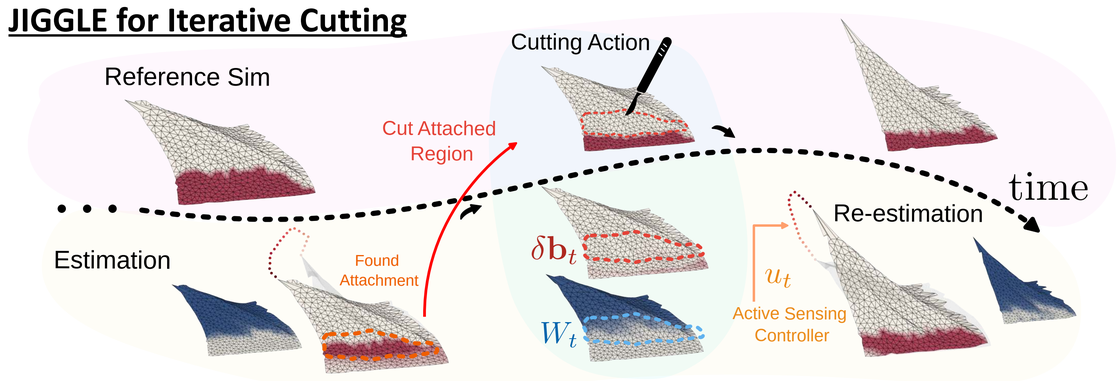


Constrained Entropy minimization via Uncertainty Weighted Displacement

Maximization: L_D

1. Sample large actions: $\mathbb{S} = \{s_1, s_2, \ldots, s_I\}$
2. Iteratively update large actions: $s_i = s_i - \alpha \nabla_{s_i} L_D$
3. Select best large action: $s_i^* = \arg\min_{s_i \in \mathbb{S}} L_D(\mathbb{S})$
4. Take small step towards large action: $u_t^* = u_{t-1} + \gamma \frac{s_i^* - u_{t-1}}{||s_i^* - u_{t-1}||}$

JIGGLE for Iterative Cutting



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