



Learning Contact-Conditioned Partitions for Uncertainty Calibration in Model-Based Planning (COPA, 2026)

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1 – Motivation

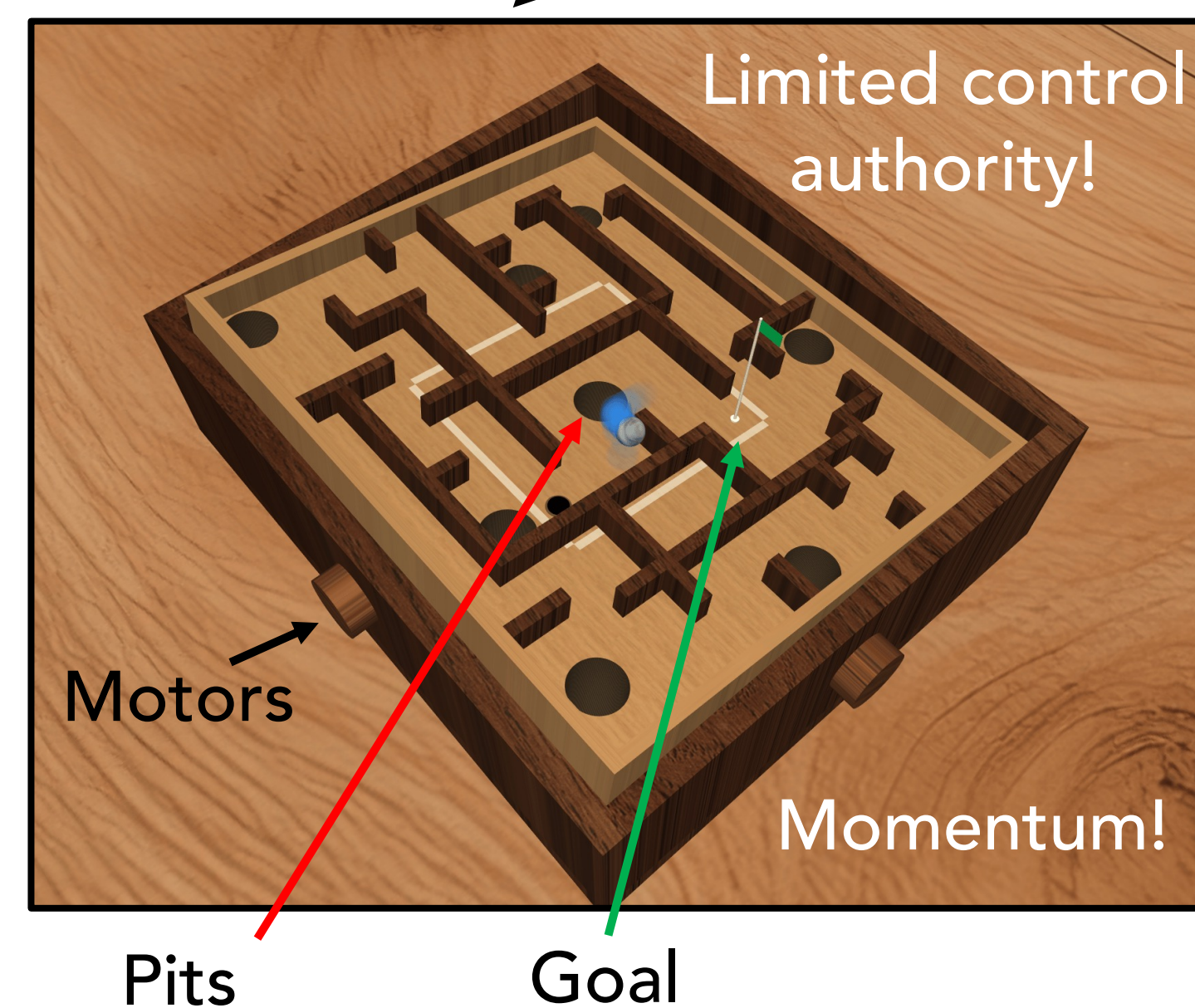
Contact changes the geometry of motion uncertainty.

Probabilistic uncertainty quantification guarantees:

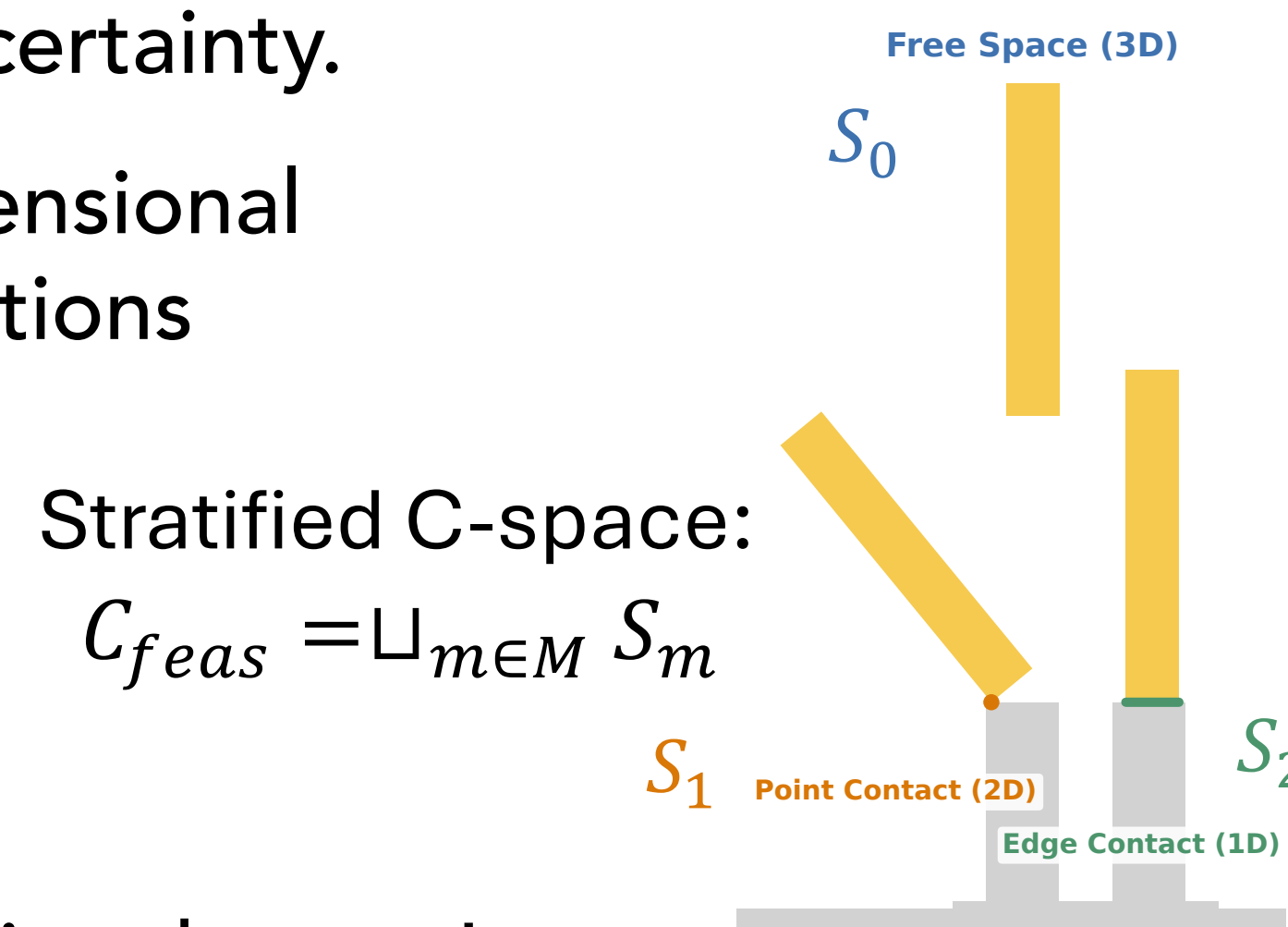
$$\mathbb{P}(c_{t+1} \in \hat{c}) \geq (1 - \alpha)$$

C-space set

Model mismatch! & External disturbances!

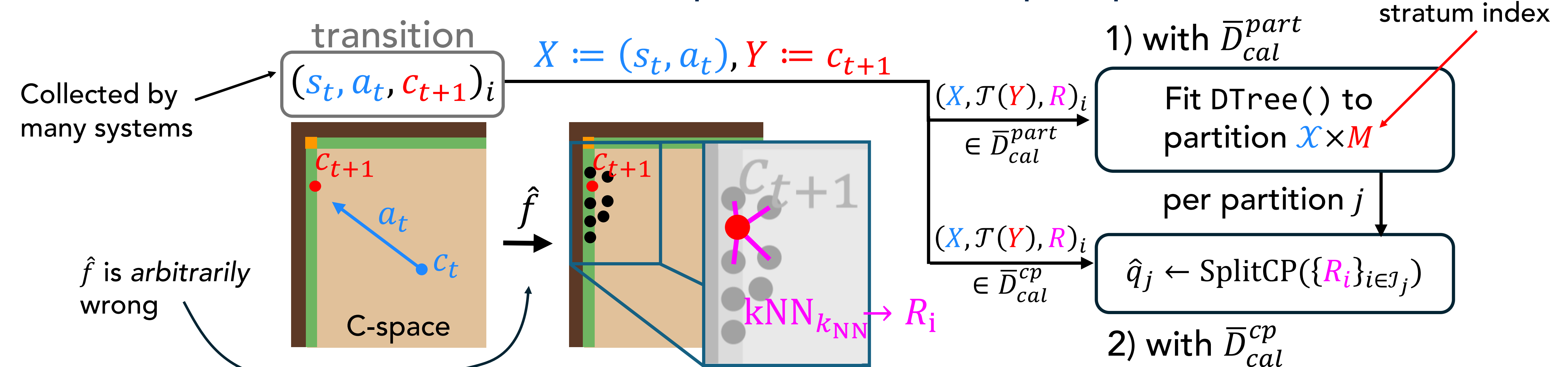


Assumption: Calibration $D_{cal} = \{(s_t, a_t, c_{t+1})\}$ and test transitions are exchangeable.
 c_t := robot configuration; $s_t := (c_t, \dot{c}_t)$; a_t := action.

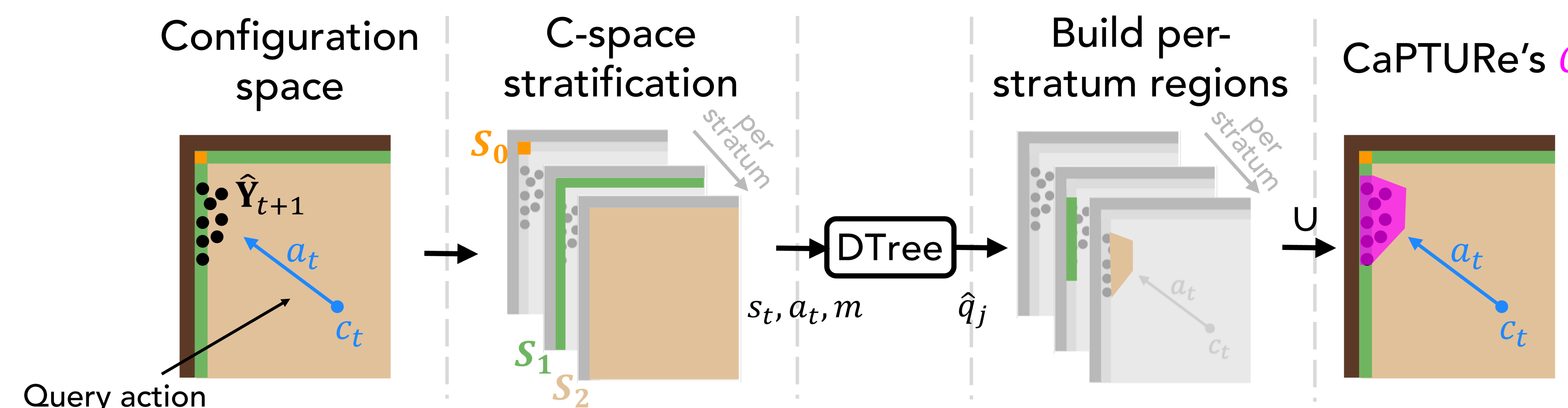


2 – Contact- and Action-Aware Uncertainty Calibration

1. *Offline:* Learn contact-aware partitions of the input space



2. *Online:* Retrieve uncertainty thresholds given candidate actions



3 – Experimental Results (Marble Maze & IsaacLab Franka Peg Insertion)

Marble: Coverage and efficiency (>400k transitions)

Metric	Stratum	LUCa	PCP	Ablation w/o stratum label	CaPTURE
Empirical Coverage (%)	All Strata	90.9	90.0	90.1	90.2
	Free Space (2D)	83.4	76.4	83.7	90.0
	Edge (1D)	94.4	96.4	93.1	90.2
	Corner (0D)	96.5	99.0	94.8	90.6
Avg. C-space Volume (ratio) ↓	All Strata	1.48	0.71	0.86	1.00

White is the 90% target; red is below, blue is above; darker tint means farther from target. C-space volume is relative to CaPTURE.

Overconfident uncertainty estimates → robot falls into pit

Marble: Planning over 6 maps (30 runs each).

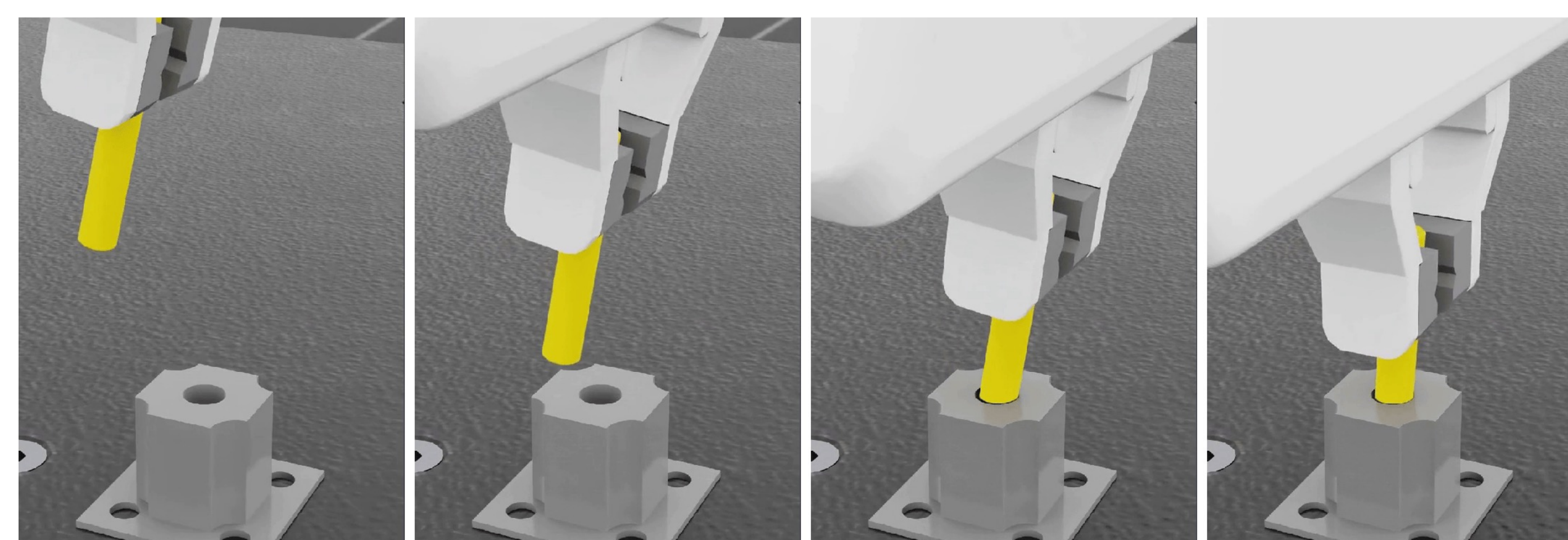
Metric	Particle NoCP	PCP	LUCa	Ablation w/o stratum label	CaPTURE
Success (%) ↑	72.8	70.6	51.7	76.1	91.1
Avg. Steps (mean±std) ↓	13.2±2.4	13.9±2.3	28.5±22.3	14.8±5.2	15.6±6.8

Success means reaching Goal without falling into a pit. Time-outs occur when an episode reaches step 100.

Key Takeaways

We learn action- and contact-aware uncertainty thresholds:

- higher volume efficiency than ambient-space methods
- decision tree groups data with similar uncertainty
- post-hoc calibration layer over particle-based estimators



Peg: Coverage and efficiency (>90k transitions)

Metric	Interaction Regime	LUCa	PCP	Ablation w/o stratum label	CaPTURE
Empirical Coverage (%)	Aggregate	90.3	89.9	91.1	90.4
	Free Space (3D)	83.8	83.1	84.9	91.0
	Point Contact (2D)	96.6	96.7	97.3	90.1
	Edge Contact (1D)	93.5	93.1	94.5	90.3
Avg. C-space Volume (ratio) ↓	Aggregate	1.03	0.70	1.09	1.00

90,000 held-out transitions. White = 90% target; red below blue above (darker = farther). C-space volume relative to CaPTURE.

Overconservative uncertainty estimates → robot gets stuck

Peg: Planning over 50 initial configurations.

Metric	ParticleNoCP	PCP	LUCa	Ablation w/o stratum label	CaPTURE
Success (%) ↑	14	48	48	48	78
Avg. Steps (mean±std) ↓	39.9±13.3	38.4±13.9	41.5±16.6	43.1±15.9	28.7±8.9

Success denotes insertion within 75 controller steps (5.0 simulated seconds).