Taccel: Scaling Up Vision-based Tactile Robotics via High-performance GPU Simulation

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Unified ABD[1]-IPC[2] Simulation

Taccel performs simulation based on **Warp-IPC**, a unified implementation of ABD and IPC, with efficient implementation in NVIDIA Warp for performance.

Time integration by solving next-step states with respect to their kinematic constraints

$$\mathbf{y}^{n+1};\mathbf{x}^{n+1} = \arg\min_{\mathbf{y};\mathbf{x}} E_{\mathrm{IPC}}(\mathbf{y};\mathbf{x}),$$

$$\text{s.t.}\quad \mathbf{S}^{\mathbf{x}}\mathbf{x} = \mathbf{s}^{\mathbf{x}} \quad \text{and} \quad \mathbf{S}^{\mathbf{y}}\mathbf{y} = \mathbf{s}^{\mathbf{y}}.$$

Augmented Lagrangian method applied:

$$E_{\mathrm{IPC}}^{\mathrm{AL}}(\mathbf{y};\mathbf{x}) = E_{\mathrm{IPC}}(\mathbf{y};\mathbf{x}) + \|(\mathbf{S}^{\mathbf{x}}\mathbf{x}-\mathbf{s}^{\mathbf{x}})^T\lambda^{\mathbf{x}}\|_2^2 + \|(\mathbf{S}^{\mathbf{y}}\mathbf{y}-\mathbf{s}^{\mathbf{y}})^T\lambda^{\mathbf{y}}\|_2^2$$

Unified IPC energy[3] for soft and affine bodies:

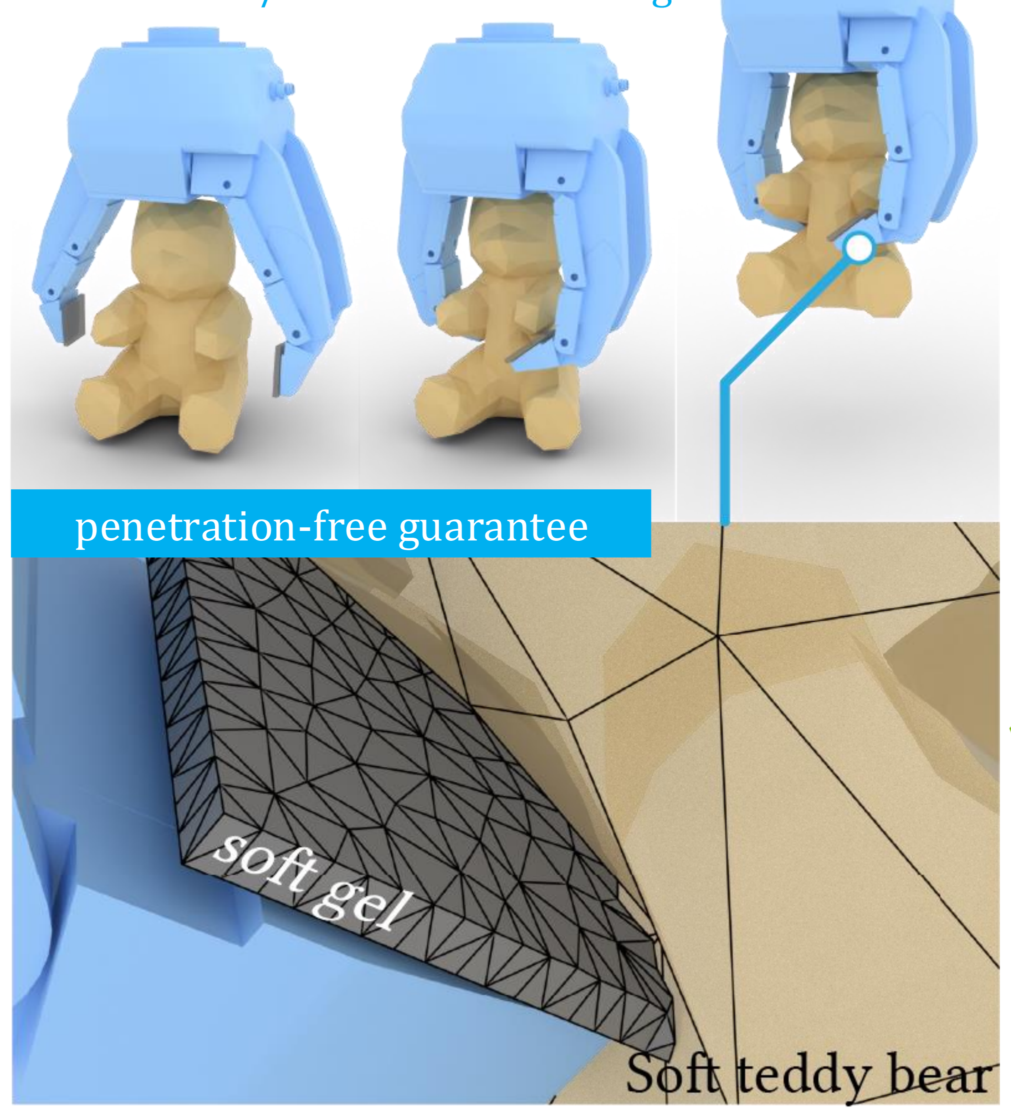
$$E_{\mathrm{IPC}}(\mathbf{y};\mathbf{x}) = E_{\mathrm{IP}}(\mathbf{x}) + E_{\mathrm{IP}}(\mathbf{y}) + \Delta t^2 B(\phi(\mathbf{y});\mathbf{x}) + \Delta t^2 D(\phi(\mathbf{y});\mathbf{x},\phi(\mathbf{y}^n);\mathbf{x}^n)$$

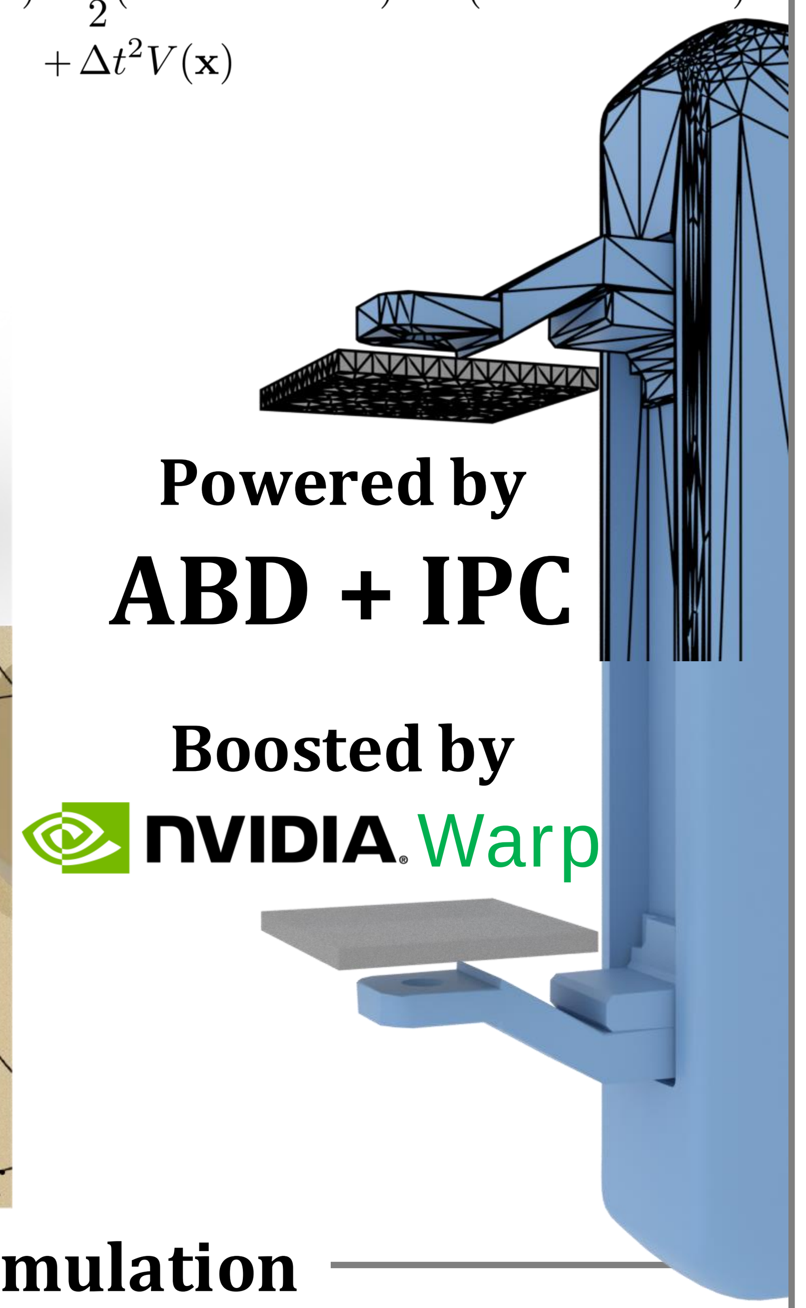
Contact / friction barrier energies

Incremental Potential energies:

$$E_{\mathrm{IP}}(\mathbf{y}) = \frac{1}{2}(\mathbf{y}-\mathbf{y}^n-\Delta t\dot{\mathbf{y}}^n)^T\mathbf{M}^{\mathbf{y}}(\mathbf{y}-\mathbf{y}^n-\Delta t\dot{\mathbf{y}}^n) + \Delta t^2 V(\mathbf{y})$$

$$E_{\mathrm{IP}}(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}^n-\Delta t\dot{\mathbf{x}}^n)^T\mathbf{M}(\mathbf{x}-\mathbf{x}^n-\Delta t\dot{\mathbf{x}}^n) + \Delta t^2 V(\mathbf{x})$$

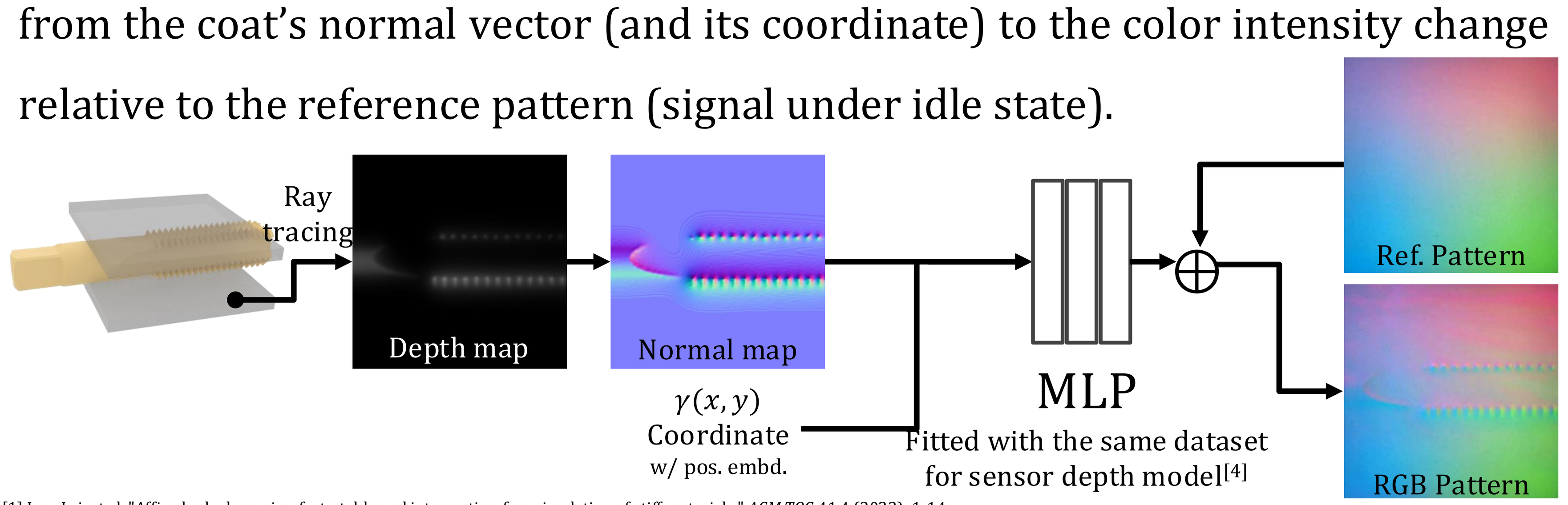




Tactile Signal Simulation

Low-resolution markers: Barycentric coordinates are established to localize each marker's position during simulation and projected to camera pixel coordinate to compute markers positions.

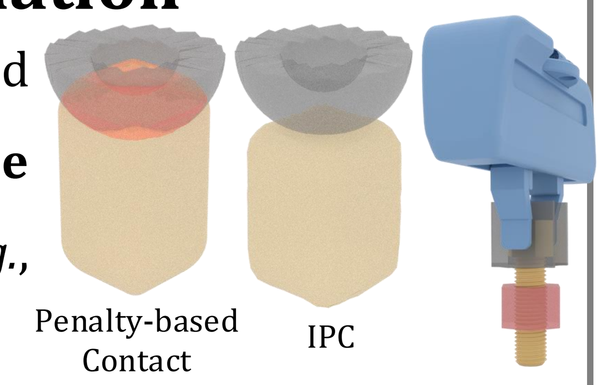
High-resolution tactile image (RGB signals): Fit a pixel-to-pixel mapping from the coat's normal vector (and its coordinate) to the color intensity change relative to the reference pattern (signal under idle state).

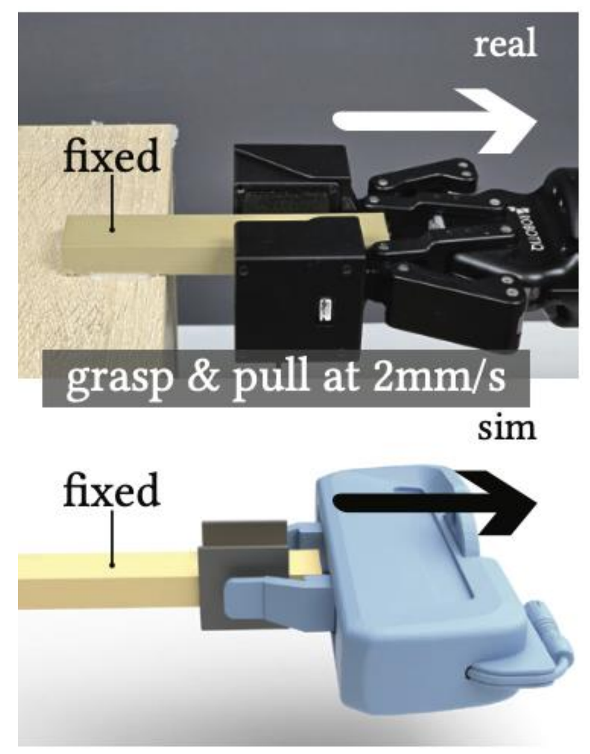


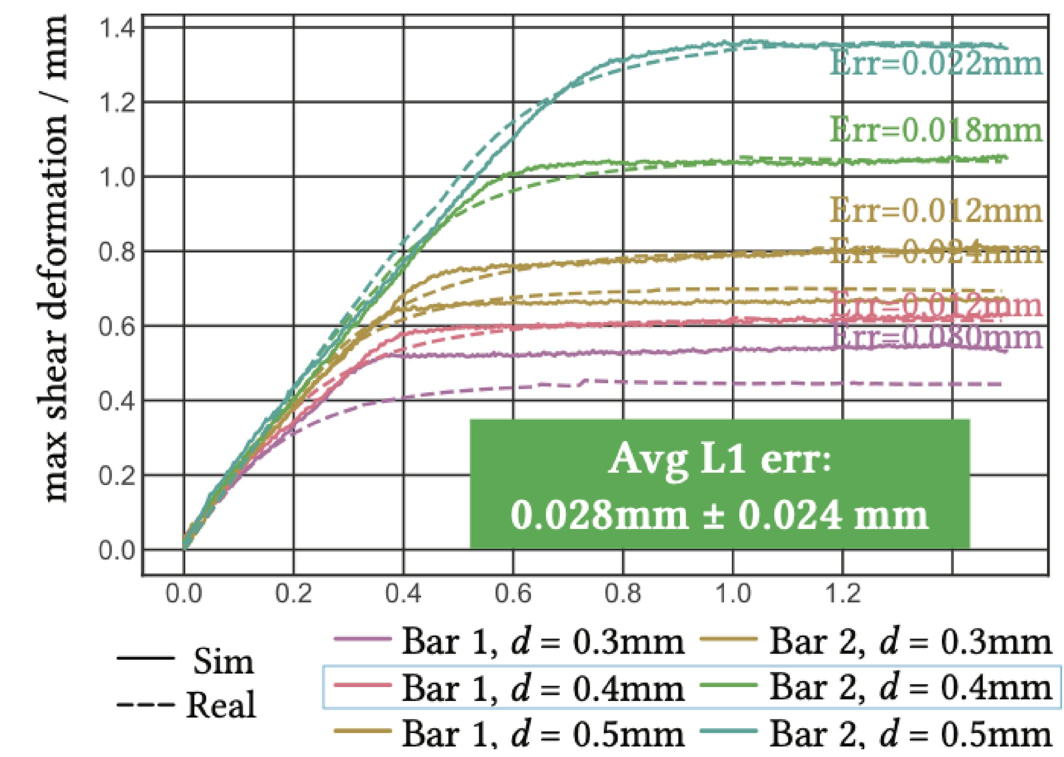
[1] Lan, Lei, et al. "Affine body dynamics: fast, stable and intersection-free simulation of stiff materials." *ACM TOG* 41.4 (2022): 1-14.
[2] Li, Minchen, et al. "Incremental potential contact: intersection-and inversion-free, large-deformation dynamics." *ACM TOG* 39.4 (2020): 49.
[3] Chen, Yunuo, Minchen Li, Lei Lan, Hao Su, Yin Yang, and Chenfanfu Jiang. "A unified newton barrier method for multibody dynamics." *ACM TOG* 41, no. 4 (2022): 1-14.
[4] Wang, Shaoxiong, Yu She, Branden Romero, and Edward Adelson. "Gelsight wedge: Measuring high-resolution 3d contact geometry with a compact robot finger." In *2021 ICRA*, pp. 6468-6475. IEEE, 2021.

Precise Physics Simulation

IPC enables **accurate physics simulation** and provides **intersection-and-penetration-free guarantee**, even in scenes with dense contact (*e.g.*, bolt-and-nut simulation).

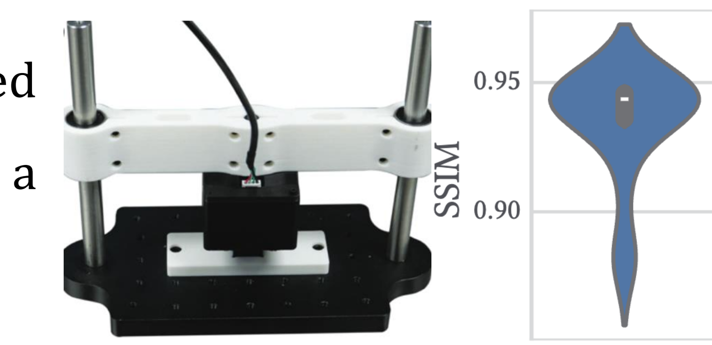


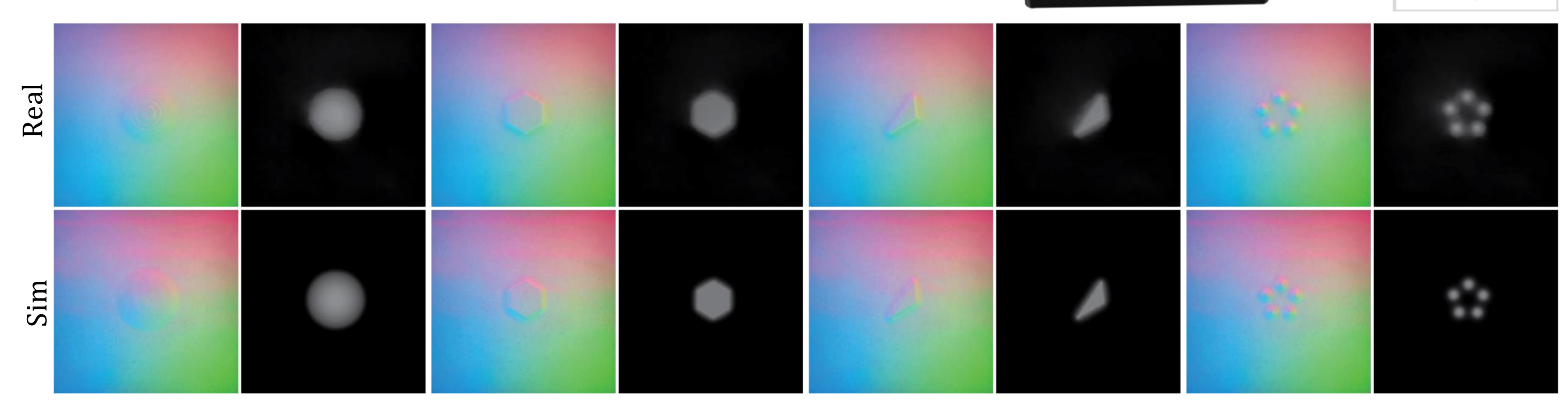




Accurate Tactile Signal Simulation

Comparison between the real and simulated tactile signals of the sensor pressing objects in a probe dataset[5] results in a high SSIM (0.93).

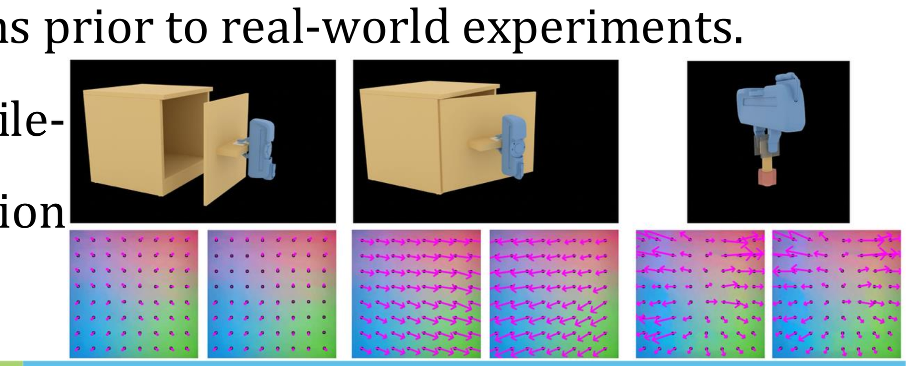


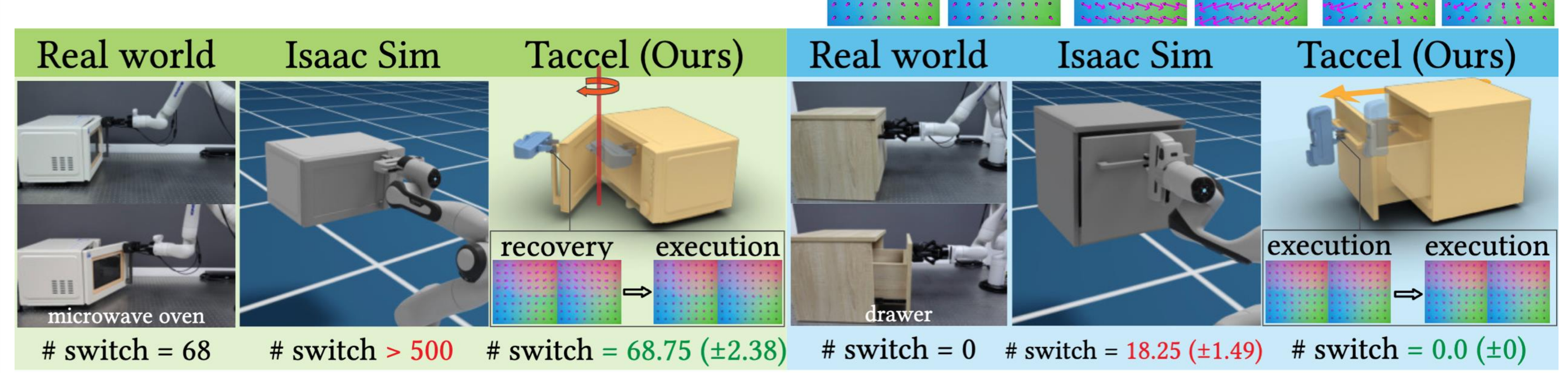


Case Study: Tac-Man[6] Simulation

Precision in physics and tactile signal simulation enables Taccel to **closely replicate real-world robotic manipulation, making** Taccel an ideal choice of validating designs, ideas, and algorithms prior to real-world experiments.

As a case study, we showcase tactile-based articulated object manipulation with Tac-Man[6].

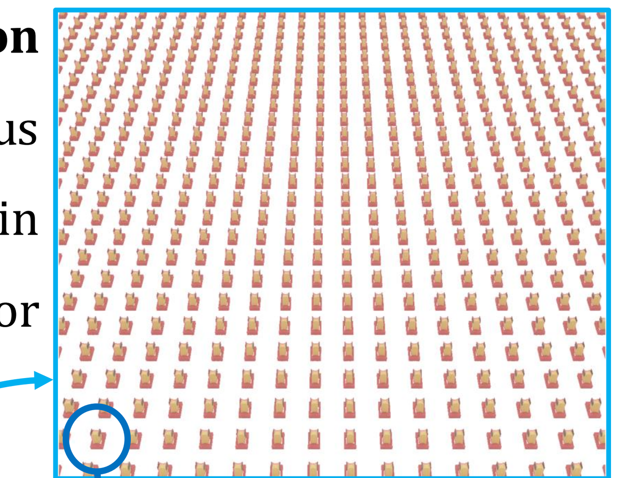


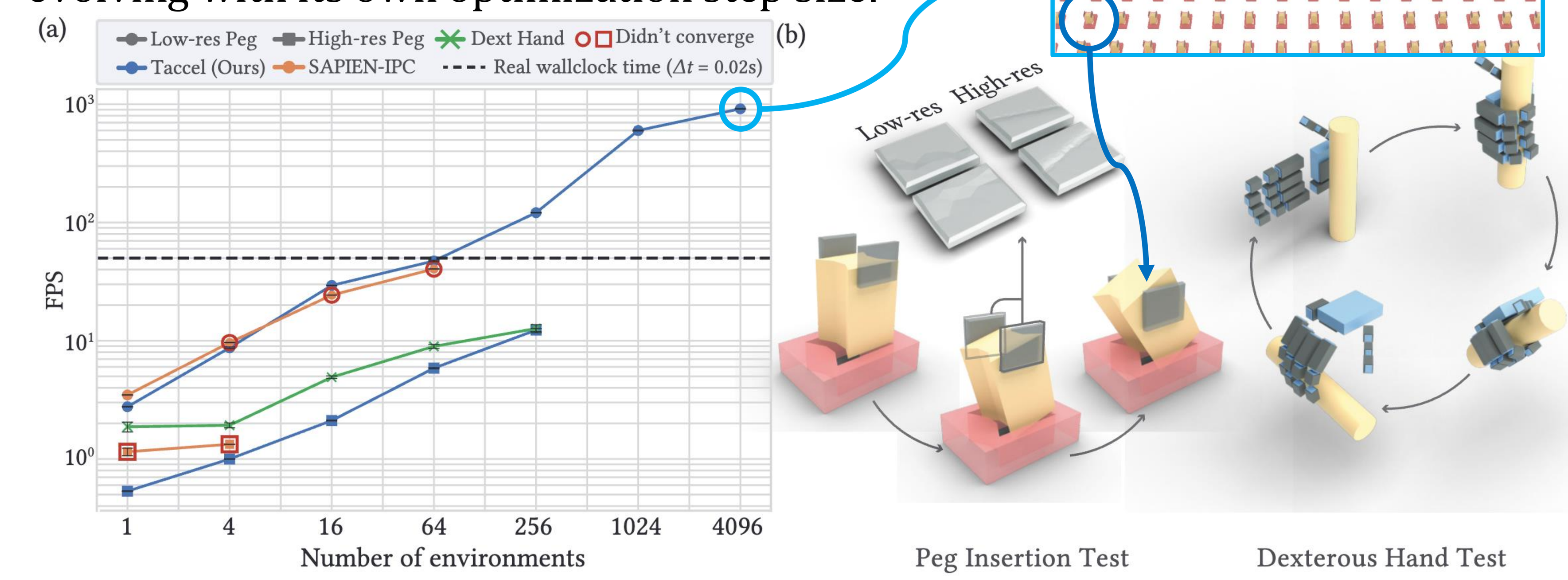


[5] Gomes, Daniel Fernandes, Paolo Paoletti, and Shan Luo. "Generation of gelsight tactile images for sim2real learning." *IEEE RA-L* 6, no. 2 (2021): 4177-4184.
[6] Zhao, Zihang, Yuyang Li, Wanlin Li, Zhenghao Qi, Lecheng Ruan, Yixin Zhu, and Kaspar Althoefer. "Tac-man: Tactile-informed prior-free manipulation of articulated objects." *IEEE T-RO* (2024).

Scaaaaaaaaaaaaaaalability

Compact data management and optimization scheme allows more parallel environments and thus the faster speeds. Environments are isolated in collision detection and step size filtering for evolving with its own optimization step size.

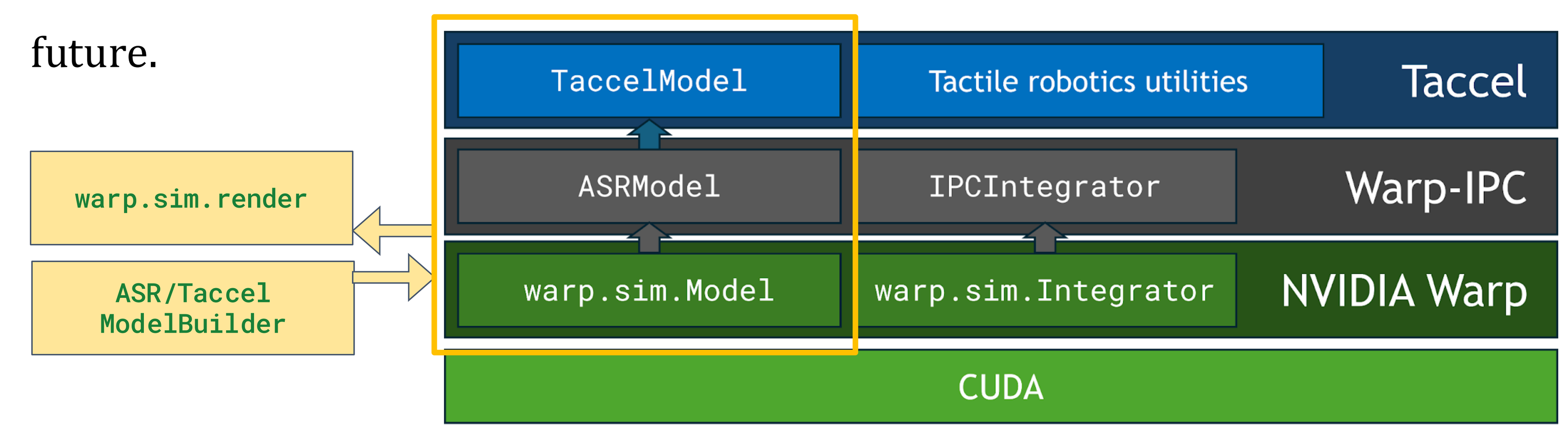




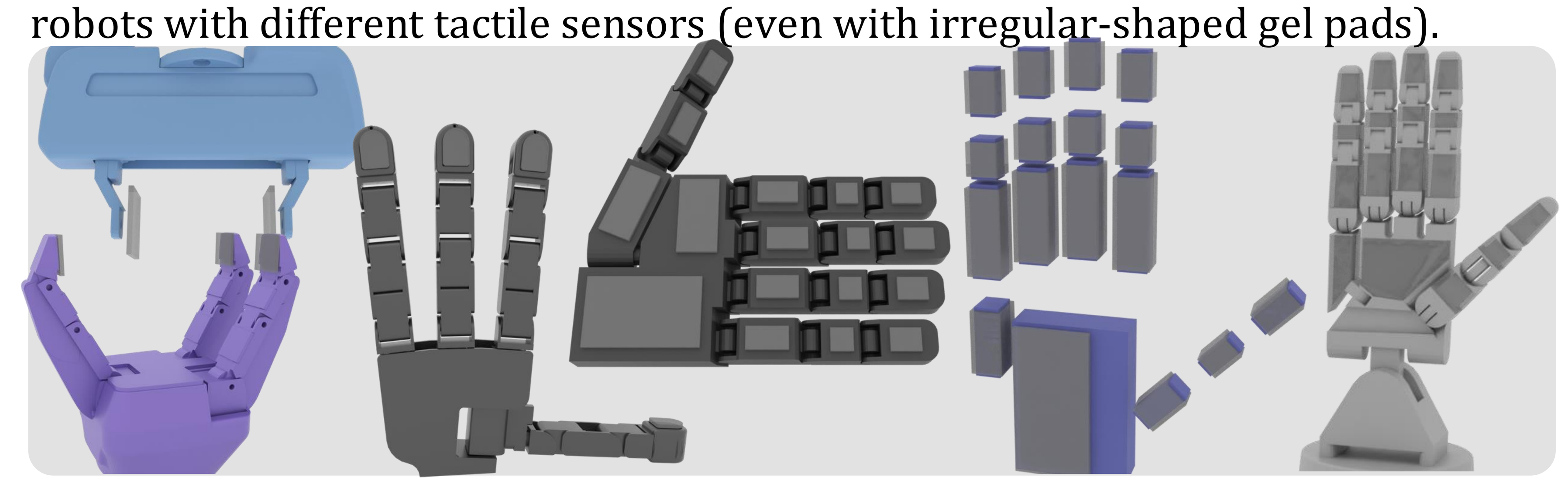
Flexibility

User-friendly APIs: Taccel provides intuitive APIs for simulation setup and control via familiar NumPy arrays or Torch tensors.

Warp-compatible infra: Taccel's infra is developed based on warp.sim modules and is on its way to be ported to NVIDIA Newton Physics in the near future.



Sensor compatibility: Taccel naturally supports the simulation of various robots with different tactile sensors (even with irregular-shaped gel pads).



Contributions and collaborations are welcome!

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