LEVERAGING UNCERTAINTY AND INTERACTIVE GUIDANCE FOR ROBOT SKILL ACQUISITION

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March 27, 2025

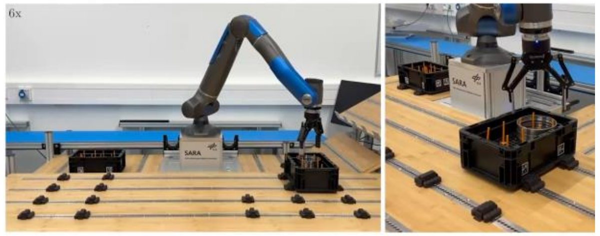
Learning real-world tasks

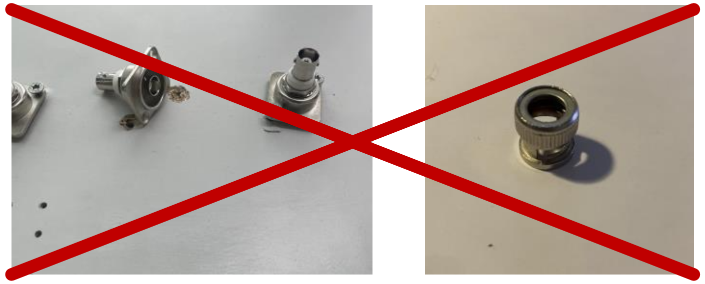
Data efficiency

- Few demonstrations
- Correct when needed (instead of teaching from scratch)

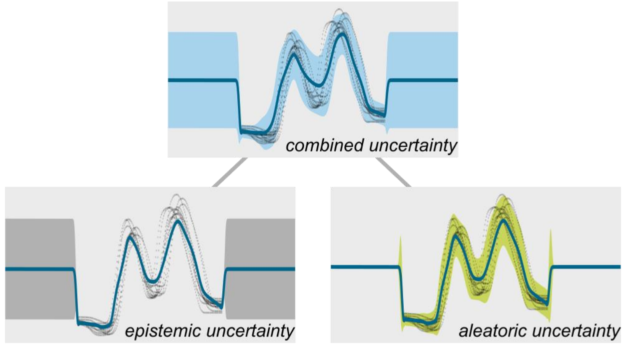
Safety

- Learning in the real world
- Leverage prior knowledge (avoid black boxes)



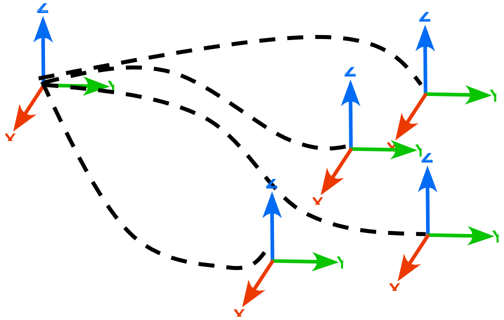


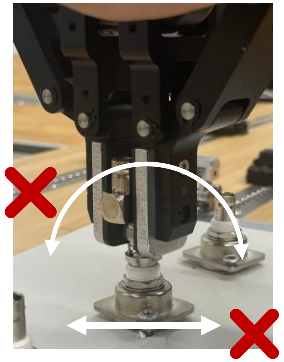
Learning real-world tasks



Uncertainty quantifications
→ Aleatoric
→ Epistemic

Task knowledge
→ Relevant object poses
→ Hard constraints





Interactive incremental learning

Reinforcement learning (RL) in the real world

Learning interactively and incrementally

$$\boldsymbol{\eta} = f(\boldsymbol{s})$$

parameters $\boldsymbol{\mu}_w, \boldsymbol{\Sigma}_w$

from demonstrations

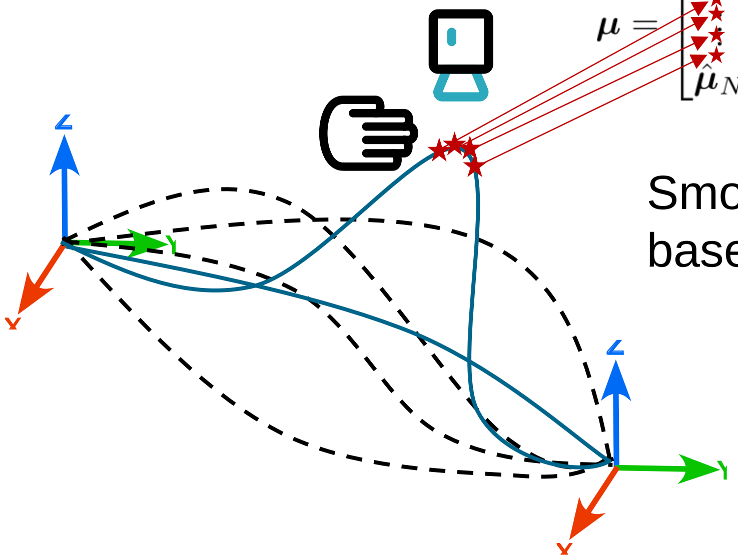
$$\arg\min_{\boldsymbol{\mu}_w} \sum_{n=1}^{N} \frac{1}{2} \left(\boldsymbol{\Theta}^\top(\boldsymbol{s}_n)\boldsymbol{\mu}_w - \hat{\boldsymbol{\mu}}_n\right)^\top \hat{\boldsymbol{\Sigma}}_n^{-1} \left(\boldsymbol{\Theta}^\top(\boldsymbol{s}_n)\boldsymbol{\mu}_w - \hat{\boldsymbol{\mu}}_n\right) + \frac{1}{2}\lambda \boldsymbol{\mu}_w^\top \boldsymbol{\mu}_w$$

Kernelized solution (non-parametric):

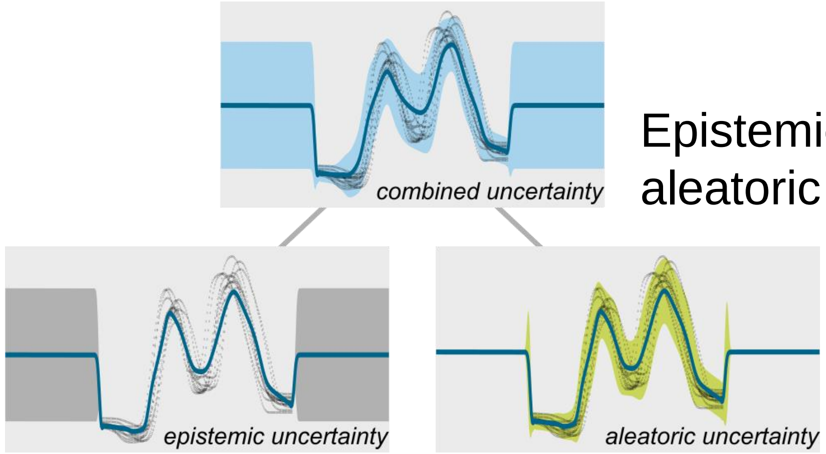
$$\mathbb{E}(\boldsymbol{\eta}(\boldsymbol{s}^*)) = \boldsymbol{k}^* \left(\boldsymbol{K} + \lambda \boldsymbol{\Sigma}\right)^{-1} \boldsymbol{\mu}$$

$$\mathrm{cov}(\boldsymbol{\eta}(\boldsymbol{s}^*)) = \boldsymbol{k}^{**} - \boldsymbol{k}^* \left(\boldsymbol{K} + \lambda \boldsymbol{\Sigma}\right)^{-1} \boldsymbol{k}^{*\top}$$

$$\boldsymbol{\mu} = \begin{bmatrix} \hat{\boldsymbol{\mu}}_1 \\ \vdots \\ \hat{\boldsymbol{\mu}}_N \end{bmatrix} \qquad \boldsymbol{\Sigma} = \begin{bmatrix} \hat{\boldsymbol{\Sigma}}_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \hat{\boldsymbol{\Sigma}}_N \end{bmatrix}$$



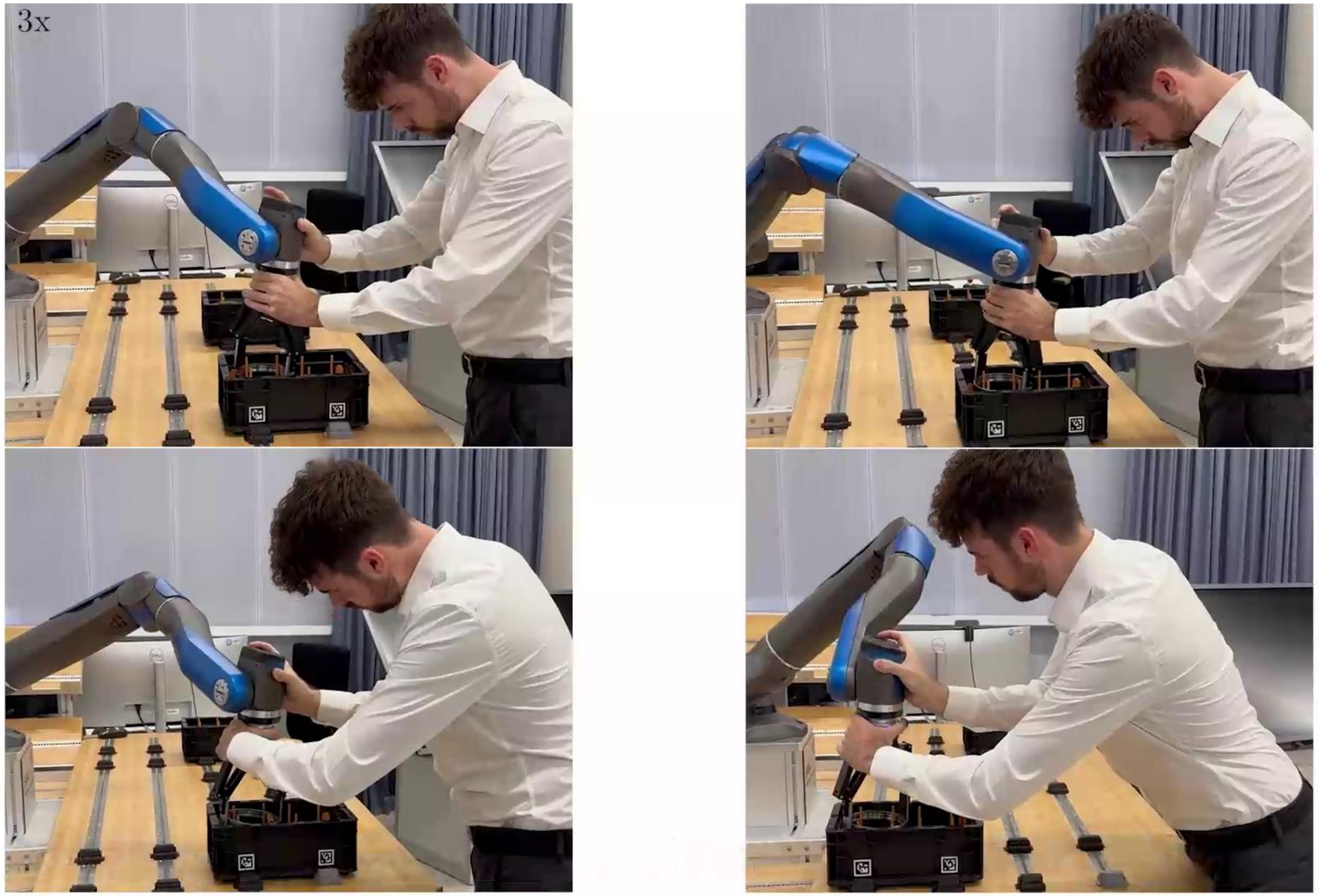
Smooth, via-point-based modulation



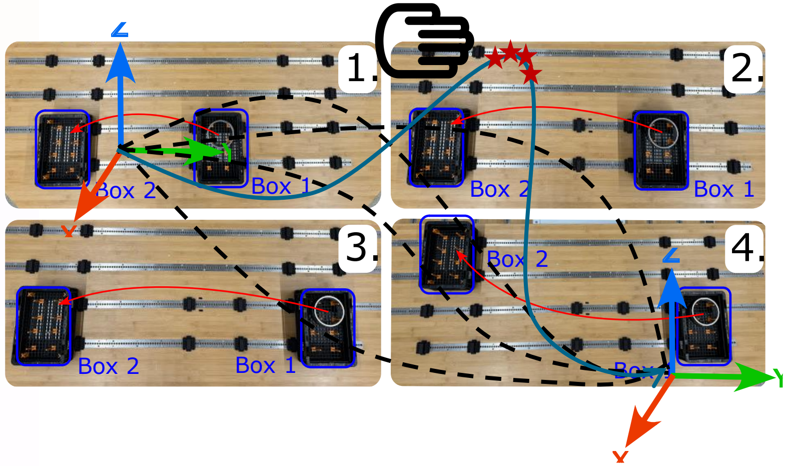
Epistemic **and** aleatoric uncertainties

[Knauer *et al.*, *Interactive incremental learning of generalizable skills with local trajectory modulation*. **RA-L** (2025)]

Learning interactively and incrementally



Markus Knauer

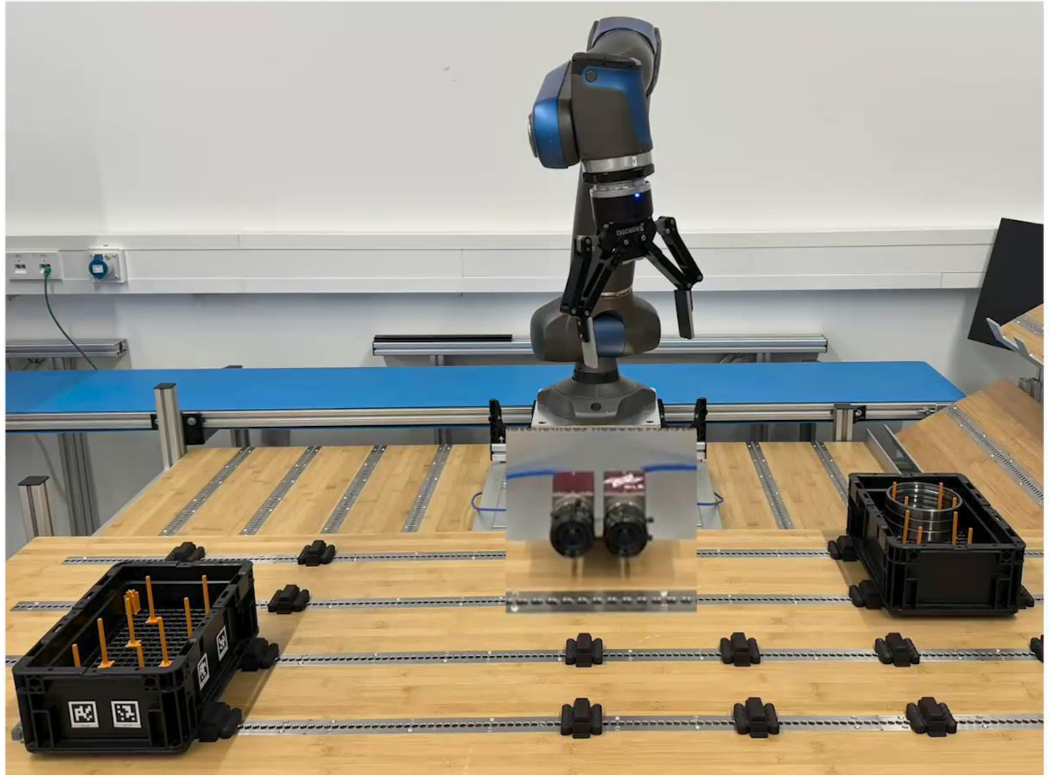


- 4 demonstrations
- Interactively:
  - Correct skills ✅
  - Add new objects
  - Extend skills

Factory of the Future X INVERSE

[Knauer *et al.*, *Interactive incremental learning of generalizable skills with local trajectory modulation*. **RA-L** (2025)]

Learning interactively and incrementally



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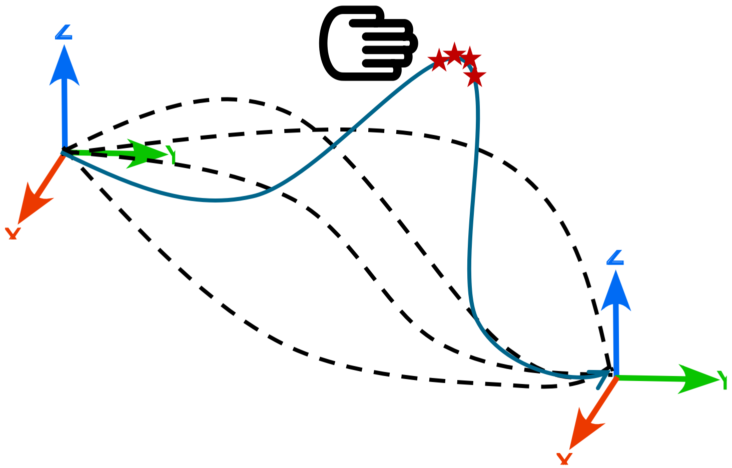

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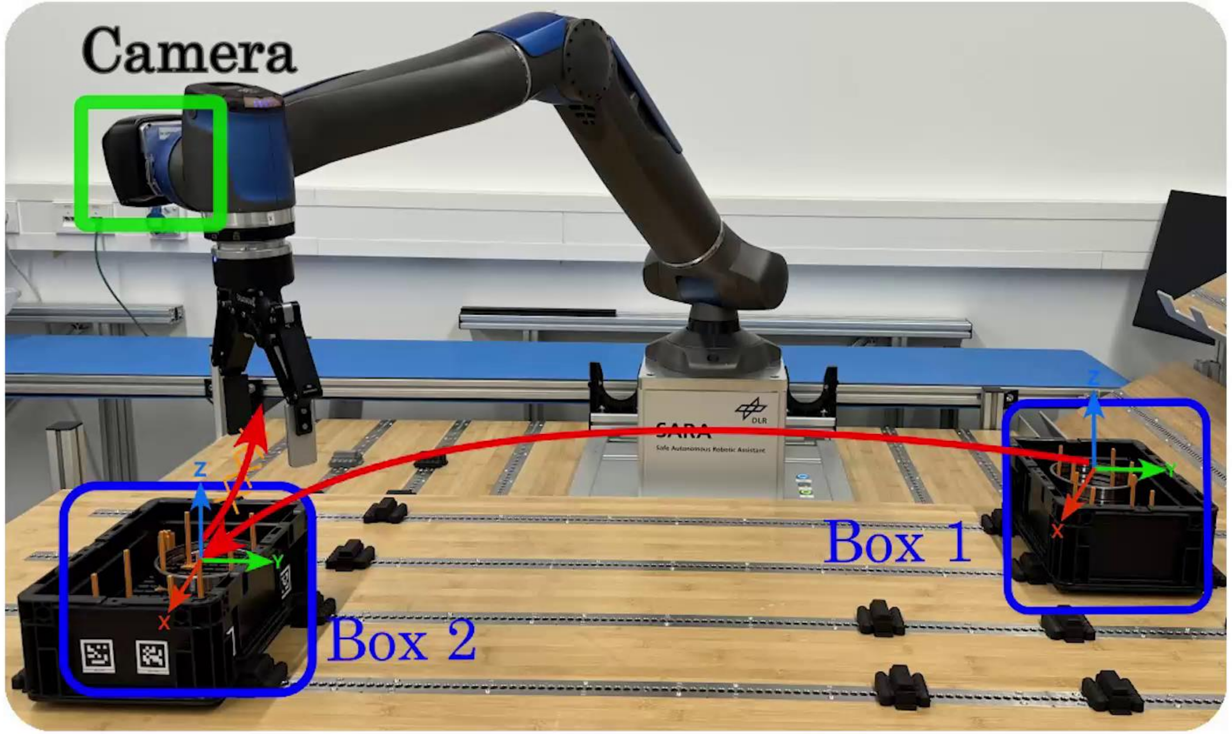
Learning interactively and incrementally



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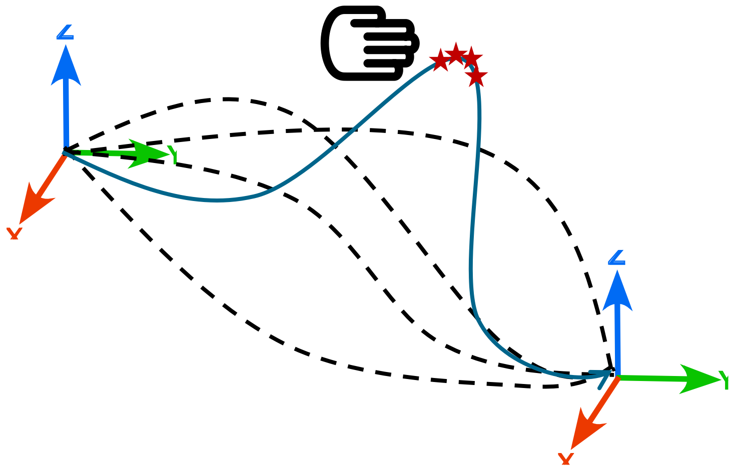

- 4 demonstrations
- Interactively:
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[Knauer *et al.*, *Interactive incremental learning of generalizable skills with local trajectory modulation*. **RA-L** (2025)]

Guided RL – unifying uncertainty awareness and hard constraints

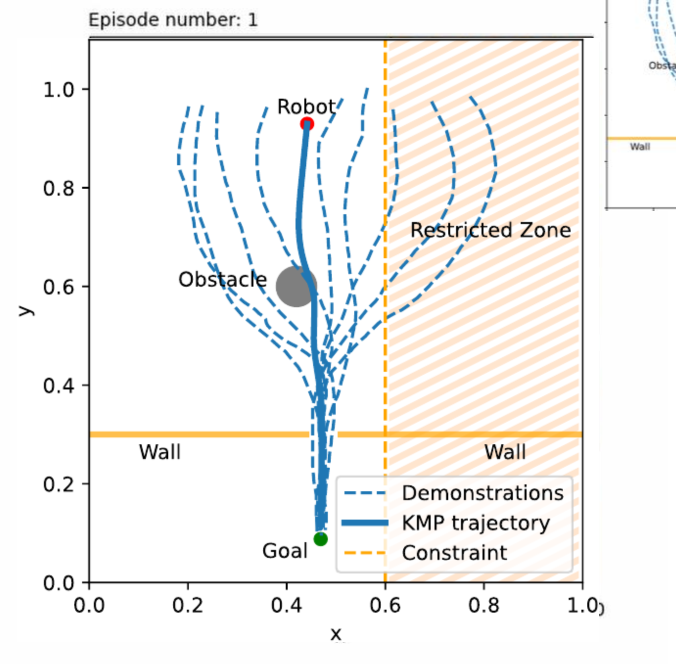
$$\arg\min_{\boldsymbol{\mu}_w} \sum_{n=1}^{N} \boxed{\frac{1}{2}\left(\boldsymbol{\Theta}^\top(\boldsymbol{s}_n)\boldsymbol{\mu}_w - \hat{\boldsymbol{\mu}}_n\right)^\top \hat{\boldsymbol{\Sigma}}_n^{-1}\left(\boldsymbol{\Theta}^\top(\boldsymbol{s}_n)\boldsymbol{\mu}_w - \hat{\boldsymbol{\mu}}_n\right)} + \boxed{\frac{1}{2}\lambda\boldsymbol{\mu}_w^\top\boldsymbol{\mu}_w + \frac{1}{2}\beta(\boldsymbol{\mu}_w - \hat{\boldsymbol{\mu}}_w)^\top(\boldsymbol{\mu}_w - \hat{\boldsymbol{\mu}}_w)},$$

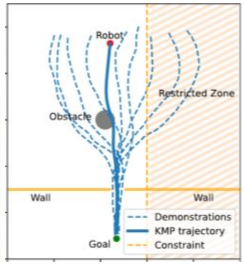
Before:

New solution:

$$\mathbb{E}(\boldsymbol{\eta}(\boldsymbol{s}^*)) = \boxed{\boldsymbol{k}^*\left(\boldsymbol{K} + \lambda\boldsymbol{\Sigma}\right)^{-1}\boldsymbol{\mu}} + \boxed{\boldsymbol{k}^*\left(\boldsymbol{K} + \lambda\boldsymbol{\Sigma}\right)^{-1}\boldsymbol{\Sigma}\bar{\boldsymbol{G}}\boldsymbol{\alpha}}$$
$$+ \boxed{\frac{\beta}{\gamma}\left(\hat{\boldsymbol{k}} - \boldsymbol{k}\left(\boldsymbol{K} + \lambda\boldsymbol{\Sigma}\right)^{-1}\hat{\boldsymbol{k}}\right)} \pi(\boldsymbol{\xi}|\boldsymbol{q})$$

RL policy



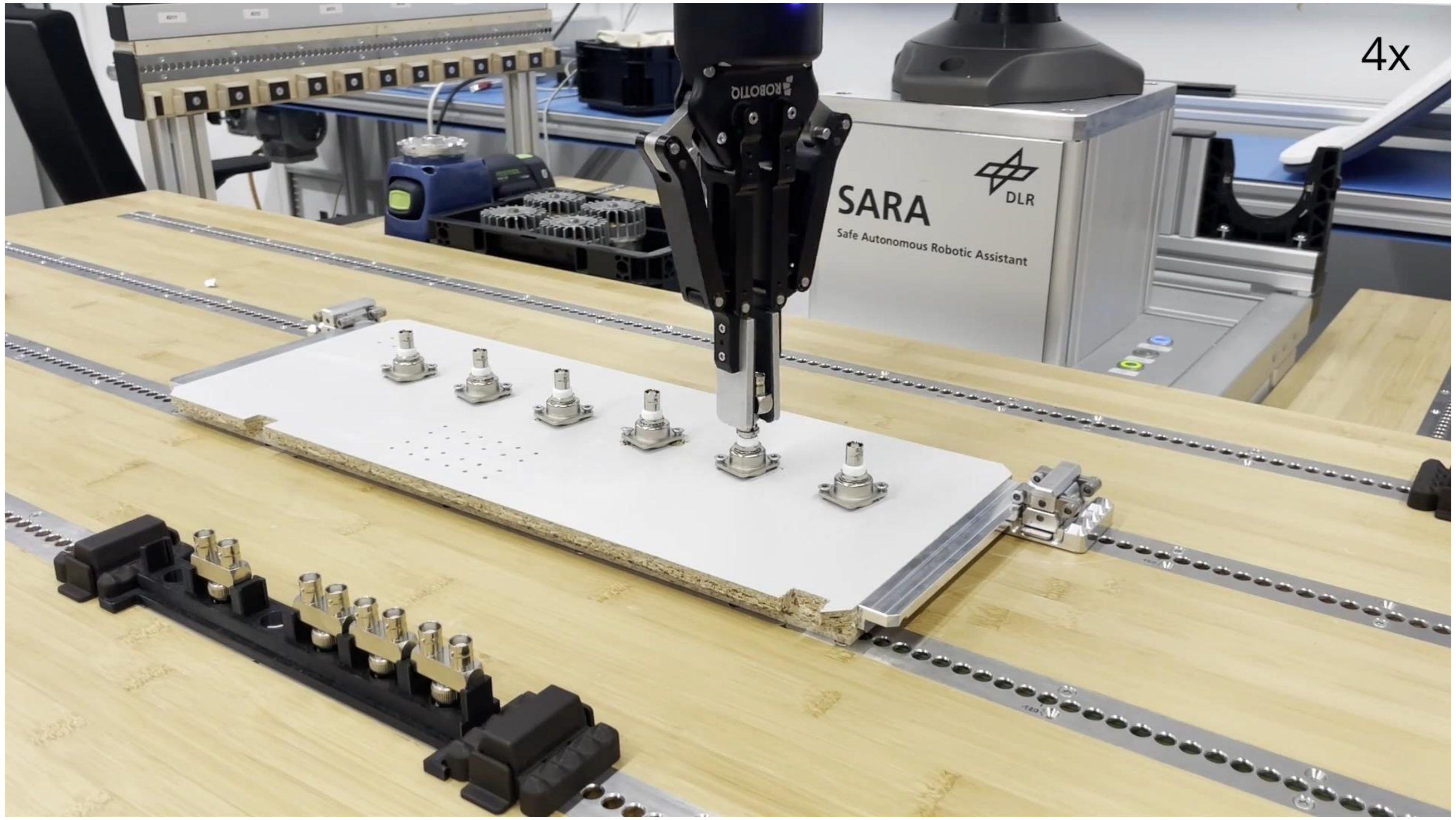


Reinforcement Learning:

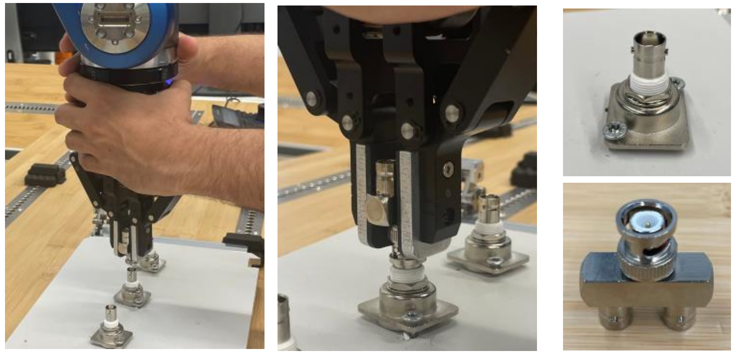
- Guided by demonstrations
- With constrained formulation
- With uncertainty aware exploration strategy

[Padalkar *et al.*, *Guiding reinforcement learning using constrained uncertainty-aware movement primitives*. **SAFE-ROL workshop, CoRL** (2024)]

Guiding RL with uncertainty + constraints



Abhishek Padalkar



Human demonstrating BNC connector insertion task to the robot

- 6 demonstrations
- Hard constraints for safety
- Effective policy search (uncertainty-aware exploration)

[Padalkar *et al.*, *Guiding reinforcement learning using constrained uncertainty-aware movement primitives*. **SAFE-ROL workshop, CoRL** (2024)]

Closing remarks

Manipulation skill learning benefits from **uncertainty quantifications** and **prior knowledge**.

Uncertainty-awareness facilitates **task generalizaition** and **enables incremental skill improvement**.

Prior knowledge such as **relevant objects** and **hard constraints** improves autonomous learning – RL in the real world becomes easier!

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