Robust AI in Surgical Robotics

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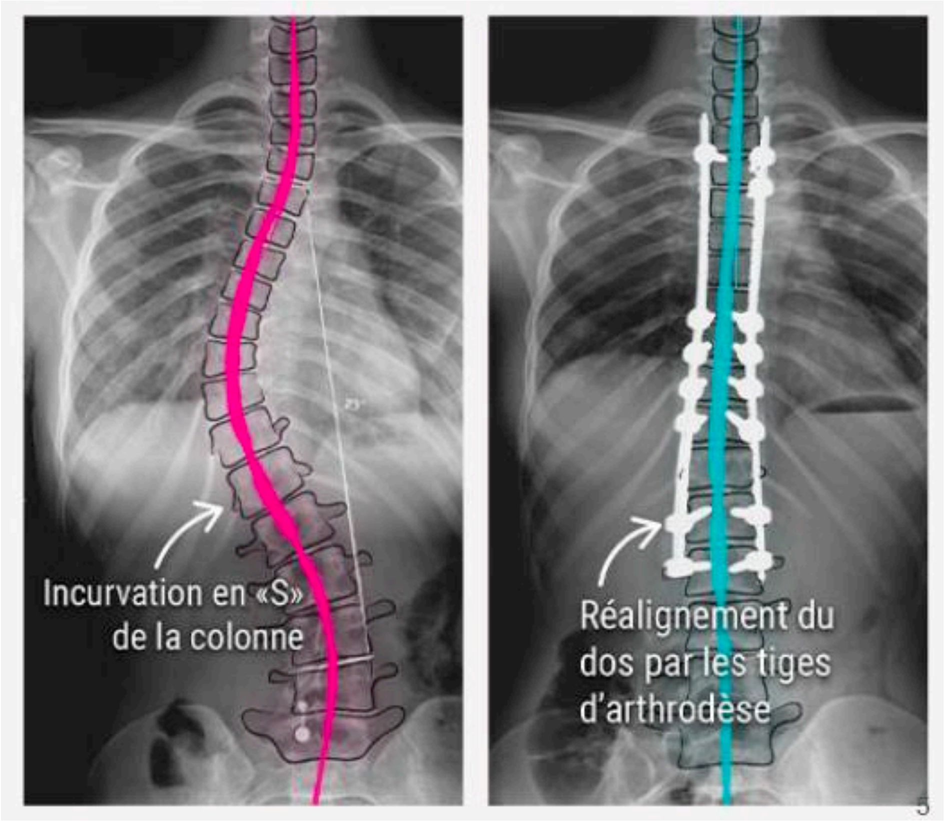
Surgical robotics: spine surgery

- ANR PRME (mono-team) project at ISIR (2024-2029)
- ClusterIA Sorbonne Univ. PostGenAI@Paris (2025-2030)
  - PAC « surgical block » with Raphael Vialle
  - Orthopaedics department at APHP, Trousseau hospital
- IUF project 2024-2030
- Ultimate goal: robot « co-manipulation » during intervention

Surgical robotics: spine surgery

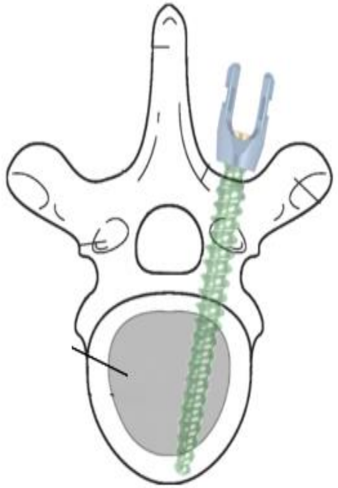
Surgical Block at APHP-Trousseau

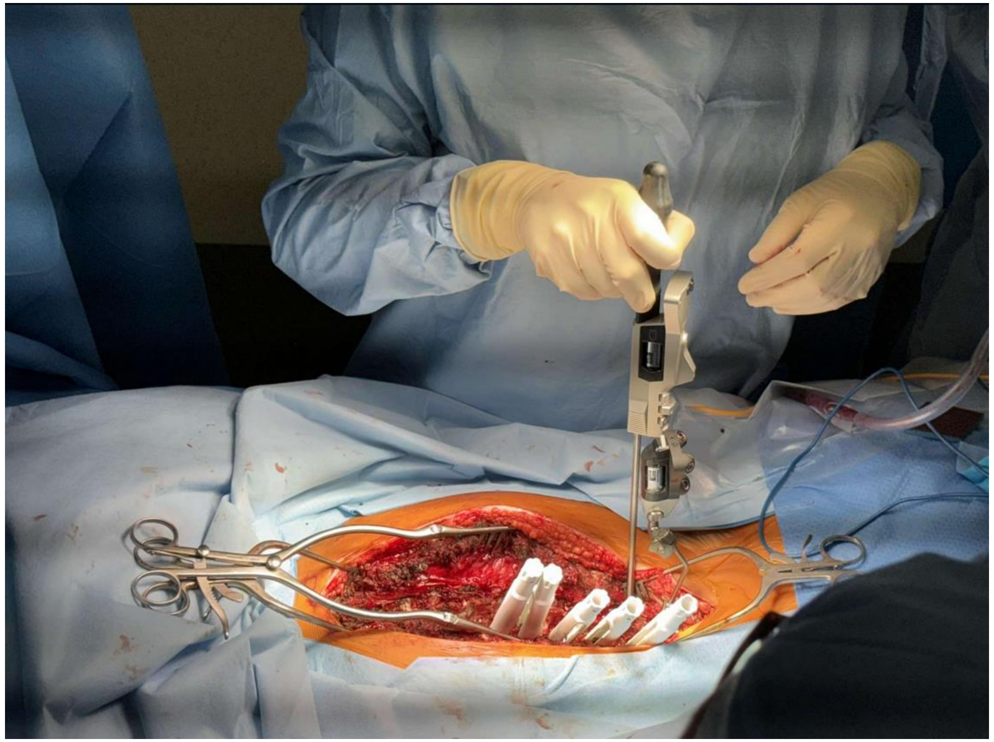
- Pre-surgery
  - Diagnosis, e.g., scoliosis



Surgical Platform at AHPH/ Trousseau

- Surgery
  - Patient on their stomach
  - Only back part of vertebrae visible
  - Fine-grained & sensitive surgery
    - Spinal cord, aorta
  - ~80% of ‘correct’ screw placement
    - Useful to correct pathology





Robust AI in surgical robotics

<u>Goal :</u> More robust platform

- AI for per-operative navigation

  ⇒ Advanced visual perception

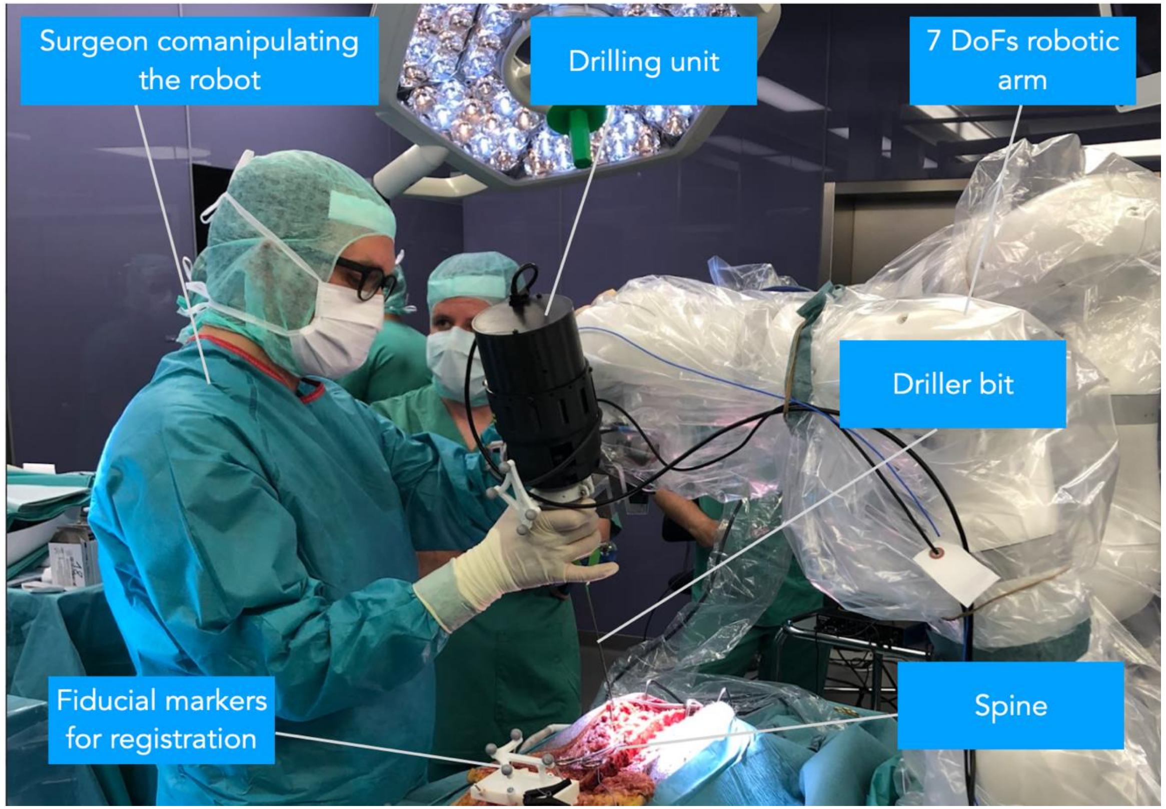
- Add co-manipulated controllers / robots

  ⇒ Language-driven interaction

  ⇒ Focus surgeons' mental load

- Uncertainty Quantification (UQ) and explainability of AI decisions

  => Enhance acceptability of patients / medical teams



Axis 1 : VLM-based planning

"Go to L5G vertebra "

⇒ **How to do so?**

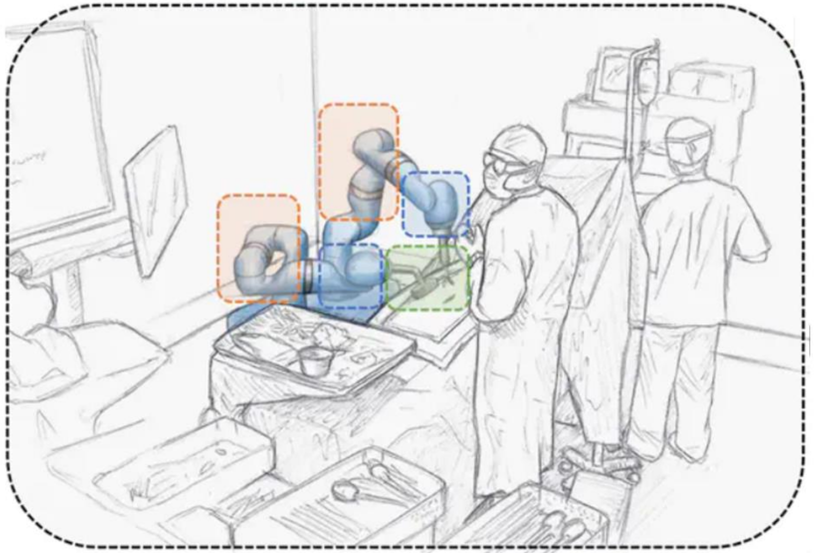
- ✓ ***Move front to the spinal column***
- ✓ *Locate L5G in the image*
- ✓ *Go to L5G*

Axis 2: Hybrid Controllers

"Move front to the spinal column"

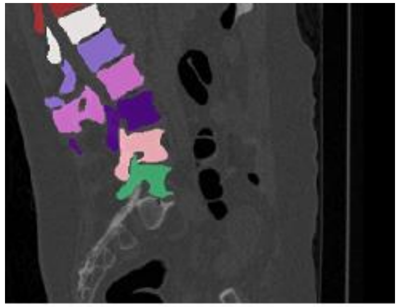
=> **Residual controllers with learned residual :** frictions, contacts, vibrations

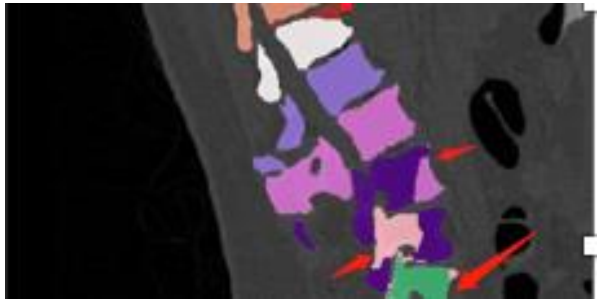
Axis 4 : AI-guided Spine surgery Visual perception / navigation



Axe 3 : Uncertainty Quantification (UQ) & Explainability

UQ in segmentation :



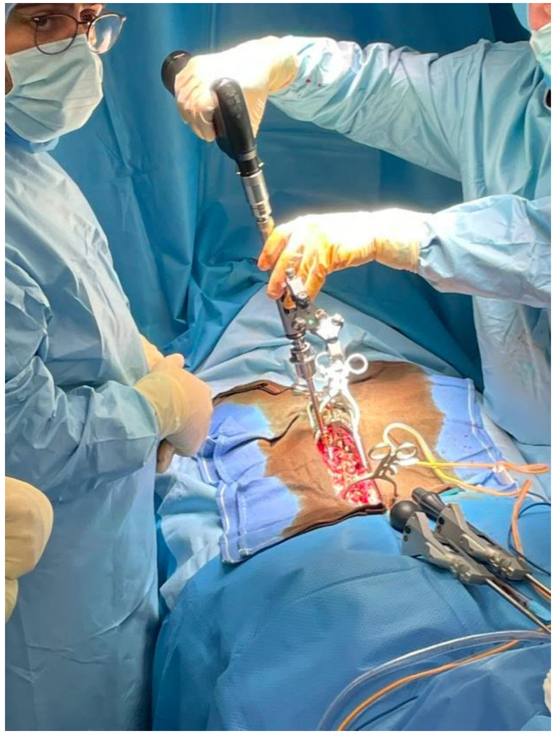


Segmentation fails

- Why?
- What do do?

Axis 4 - Navigation system at APHP / trousseau

Scan pre-per op



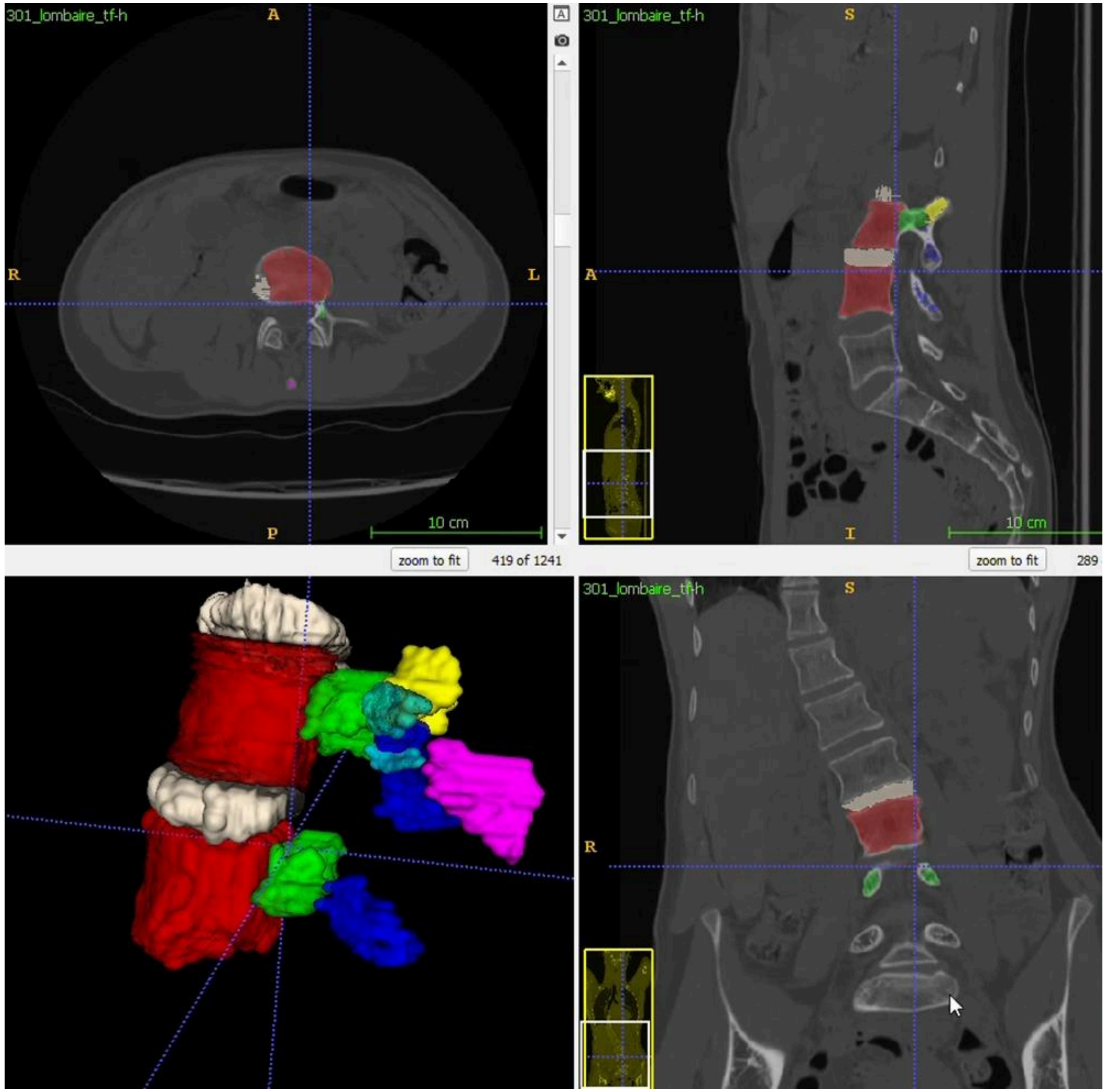
Surgery, e.g., pedicle screw insertion

Registration surgical tools <-> scan : 3D visualization

Axis 4 - Visual Perception: segmentation

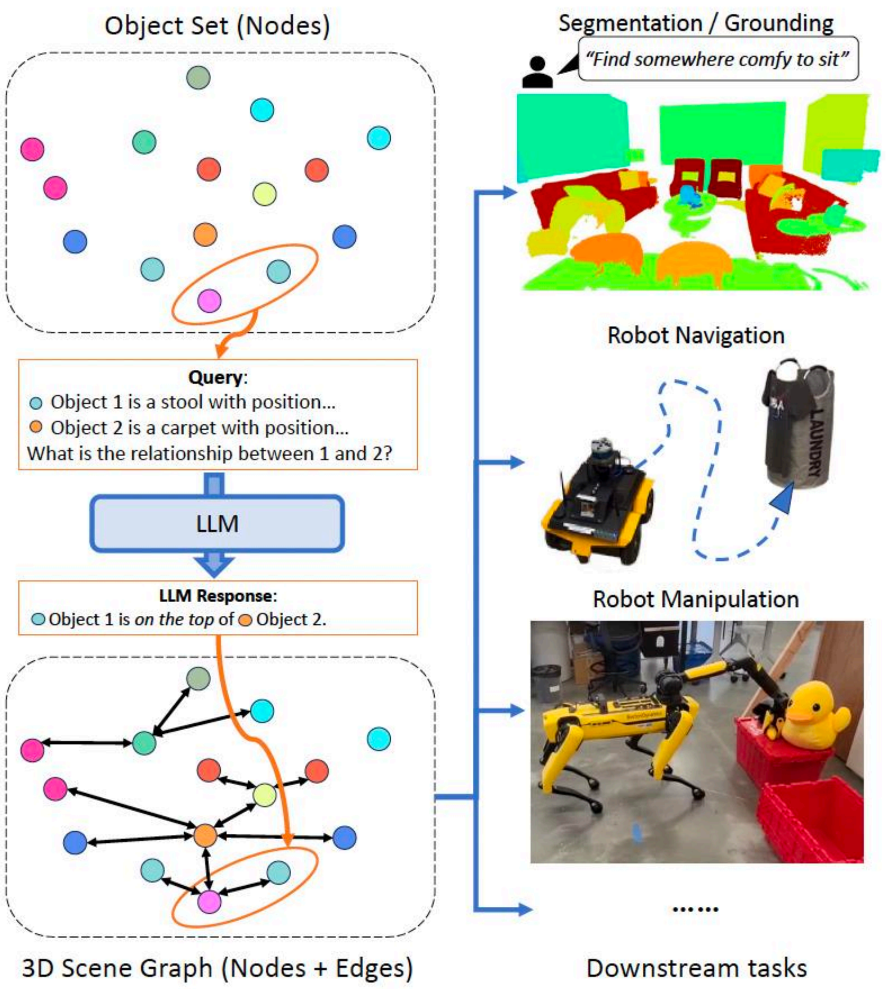
- Pre-op 3D scans AI-driven segmentation

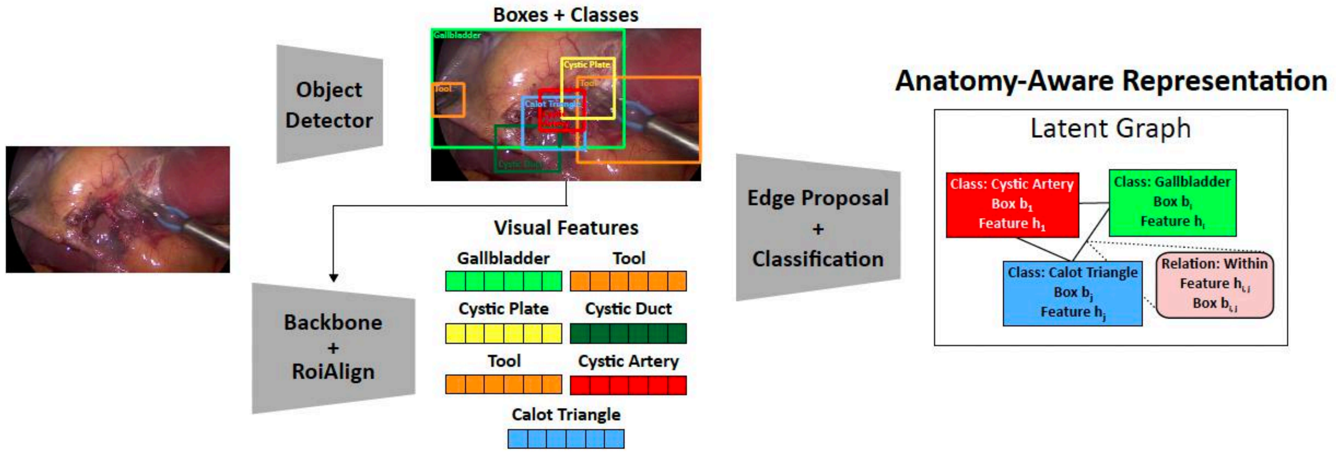
- Segment individual vertebrae + sub-structures
  - Vertebral bodies, disks, pedicles, spinous processes, vertebral laminae, Transverse processes, articular processes + spinal canals



Axis 4 - Concept graph

- Segmentation: object centric representations
- Concept graph: relation between structures
- Input for navigation, planning





Axis 1 - language-driven planning

- Make human-robot interactions smoother
- Leverage recent progress in LLMs/VLMs to represent knowledge

“Go to L5G vertebra ”

- ✓ ***Move front to the spinal column***
- ✓ *Locate L5G in the image*
- ✓ *Go to L5G*

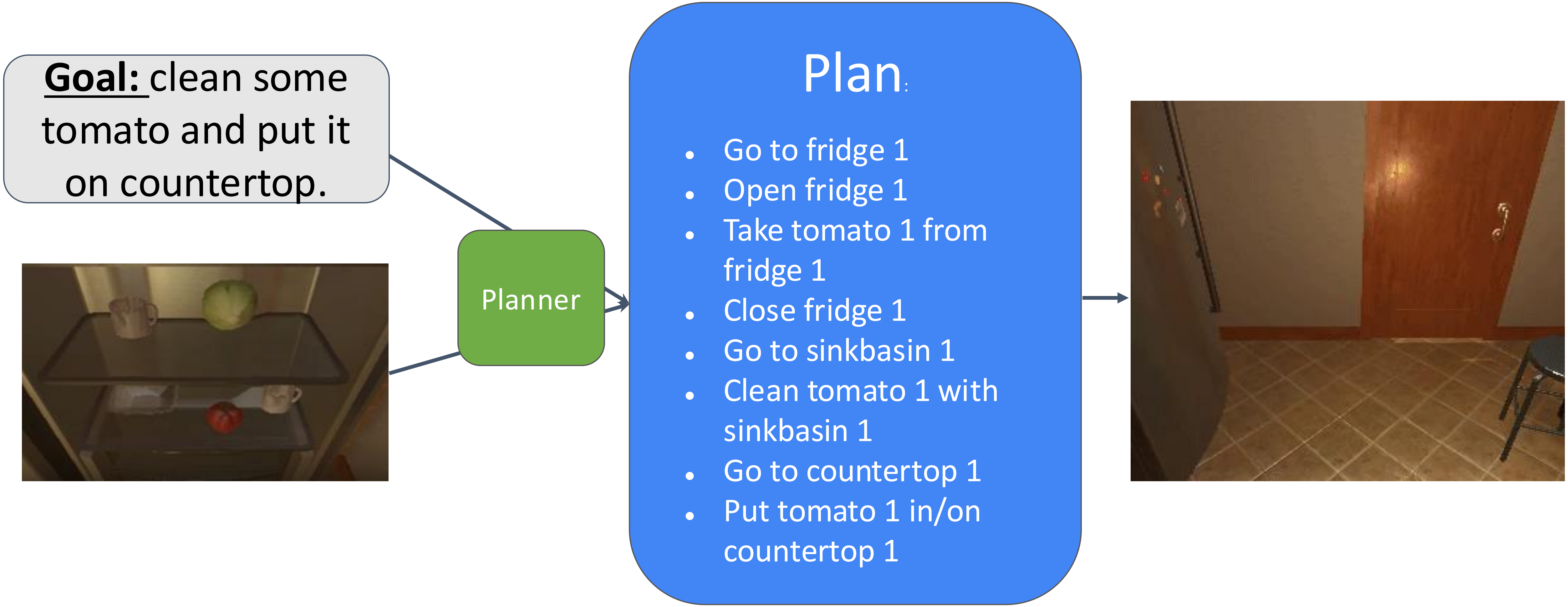
Challenges in AI

- Grounding LLMs/VLMs in the real world
- Joint training of planning and control
- Domain shift in surgical robotics

Axis 1 - ongoing works

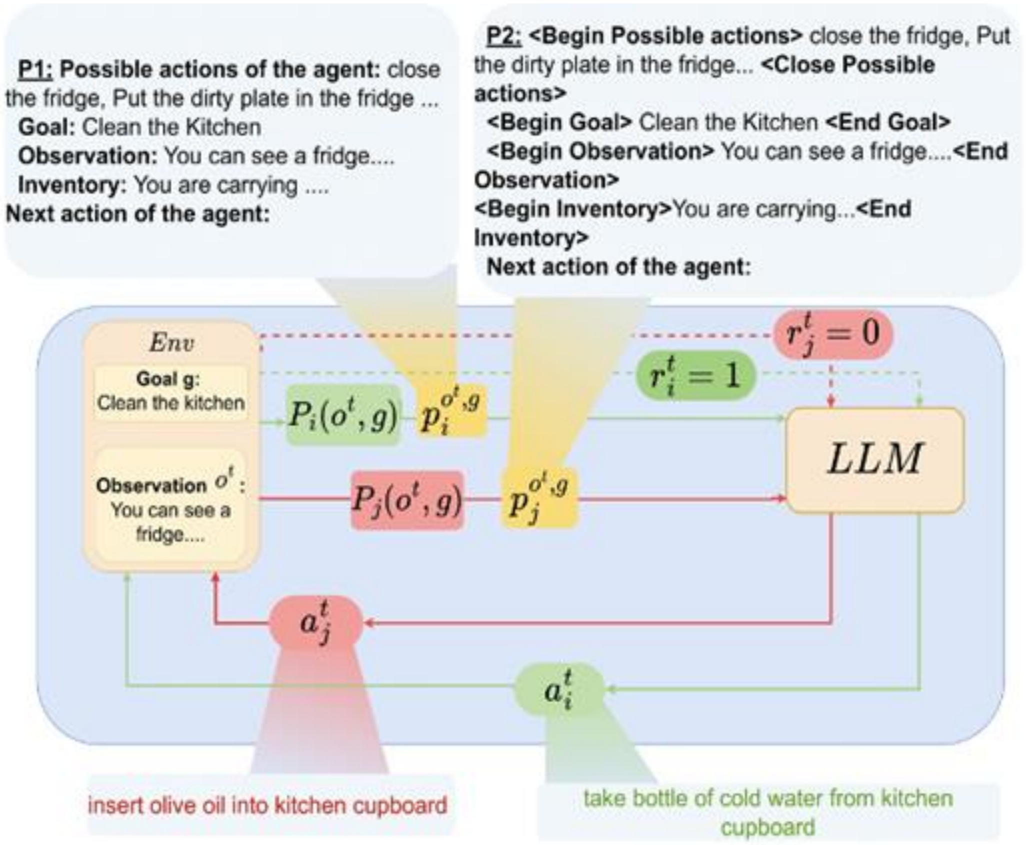
LLMs / VLMs for planning in robotics, “embodied AI”

- Instruction-based planning

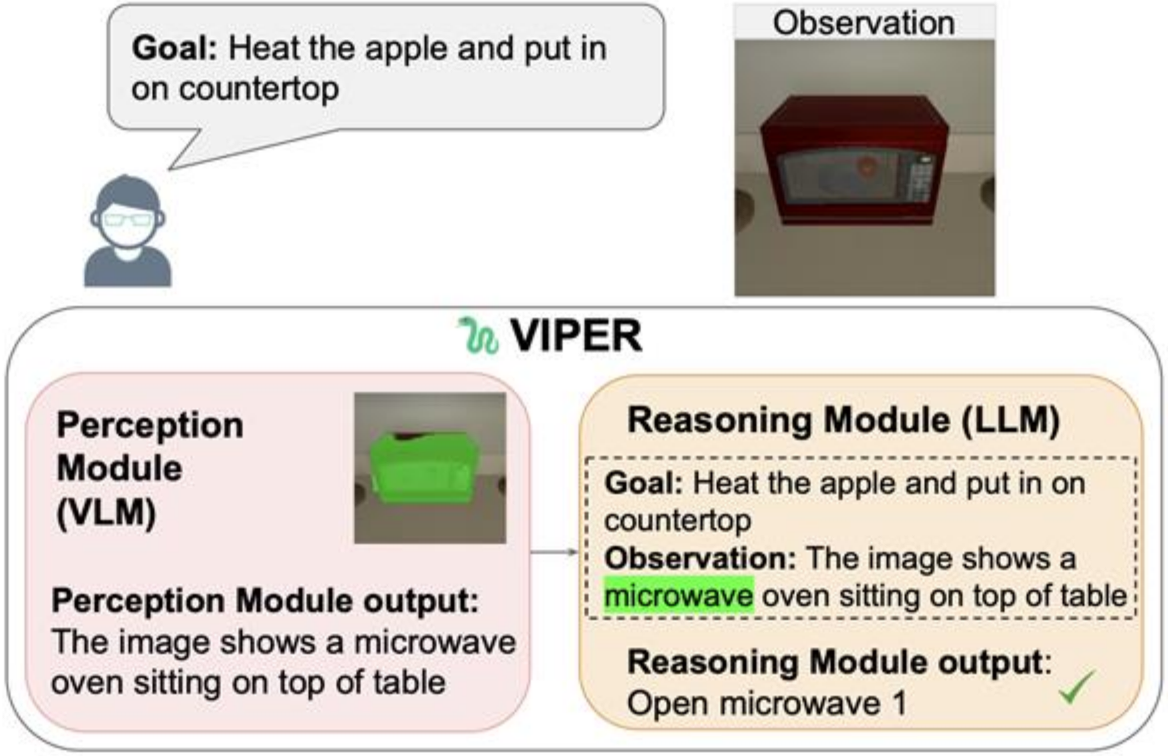


Axis 1 - ongoing works: PhD Salim Aissi

- Fine-tuning LLMs, prompt overfitting, NAACL'25
  - Solutions to mitigate the pb



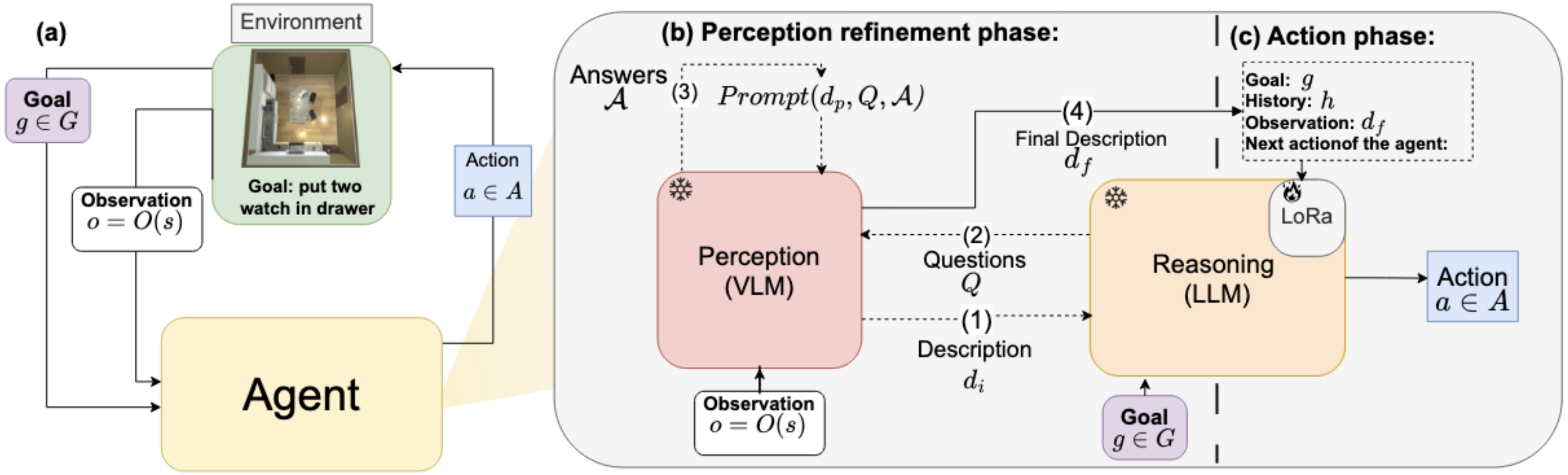
- VLMs for visual perception
  - VLM -> Text description
  - LLM for reasoning

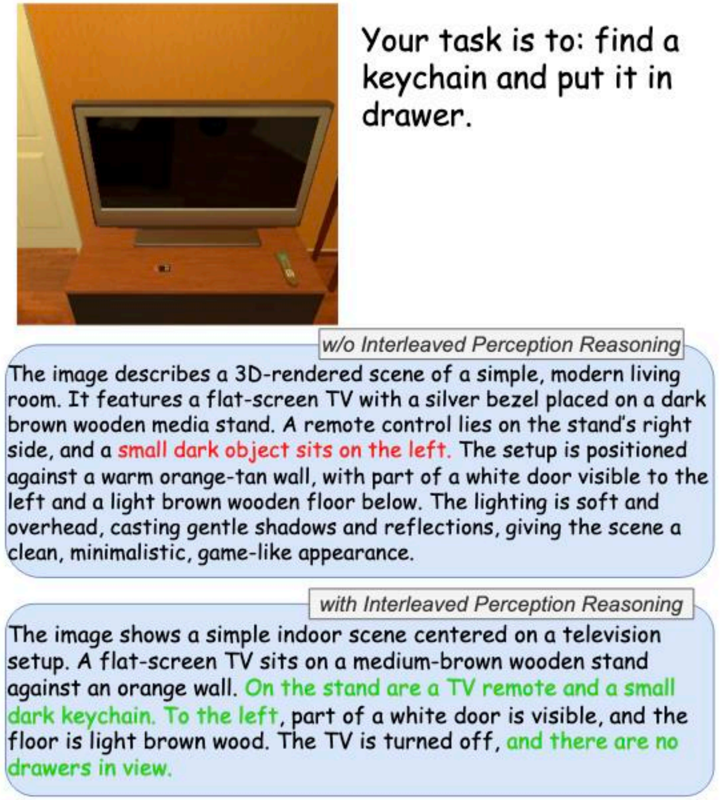


L. Soulier, O. Sigaud, C. Grislain, M. Chetouani + Flowers INRIA

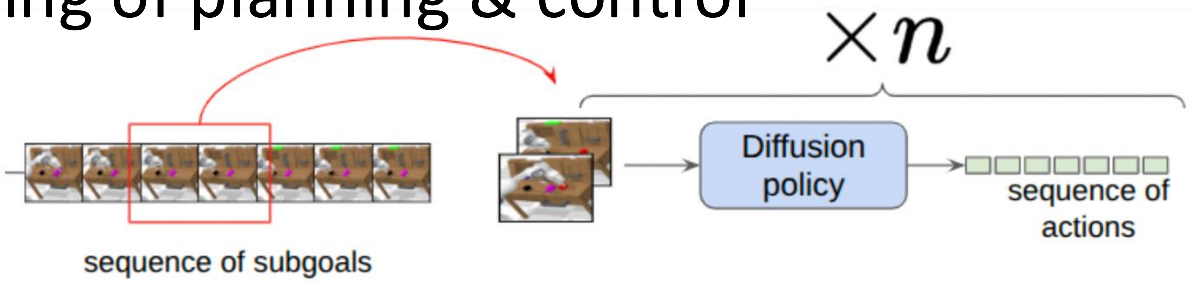
Axis 1 - ongoing works & perspectives

- Including explicit reasoning: feedback loop between reasoning -> perception: VQA





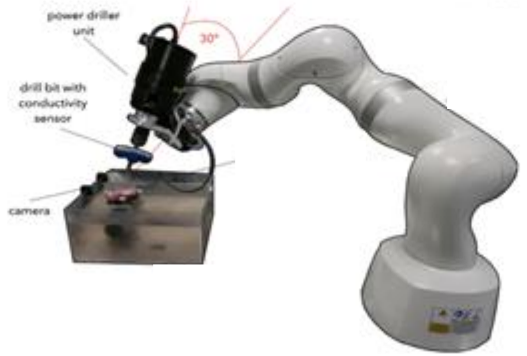
- Joint learning of planning & control

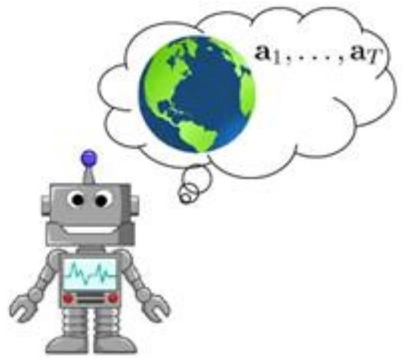


Axis 2 - hybrid controllers: PhD Zakariae El Asri

Hybrid reinforcement learning

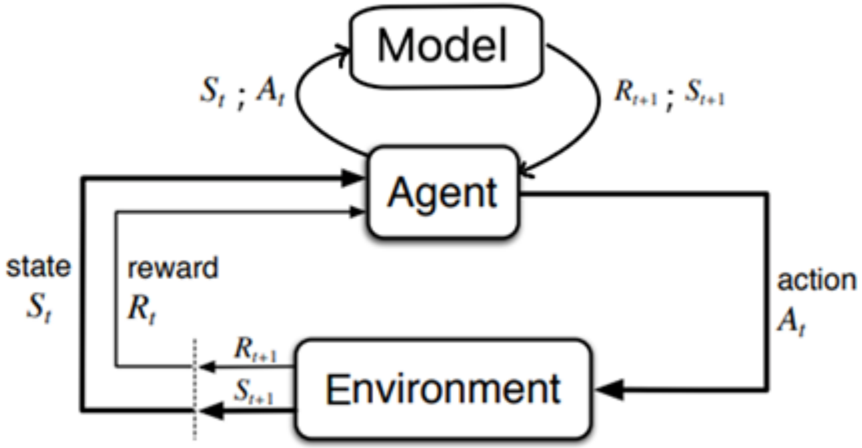
Model-based (MBRL) / model –free (MFRL)

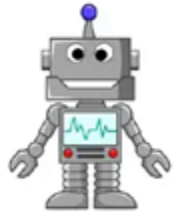




- Asymptotic performance (+)
- Sample efficiency (+)
- Time efficiency (−)

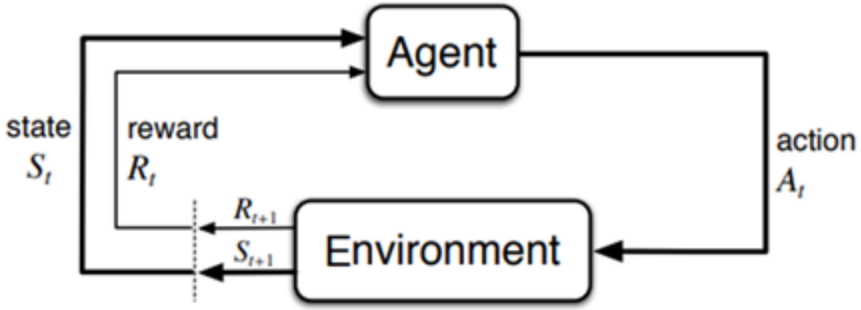
Model-Based RL





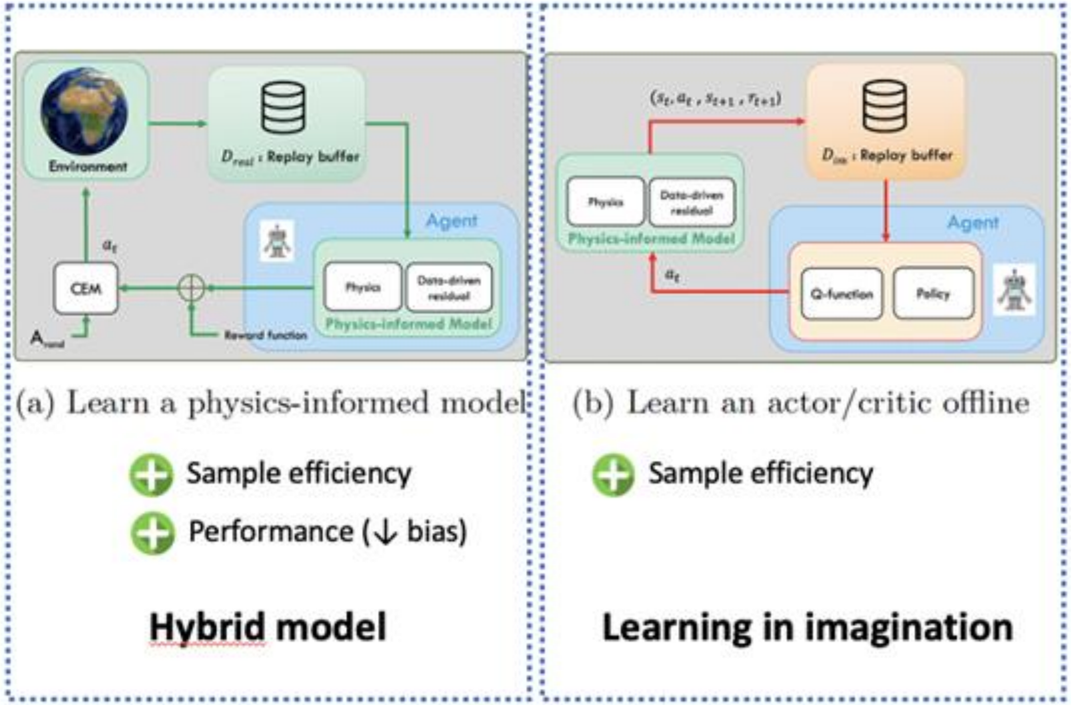
- Asymptotic performance (+)
- Sample efficiency (−)
- Time efficiency (+)

Model-Free RL

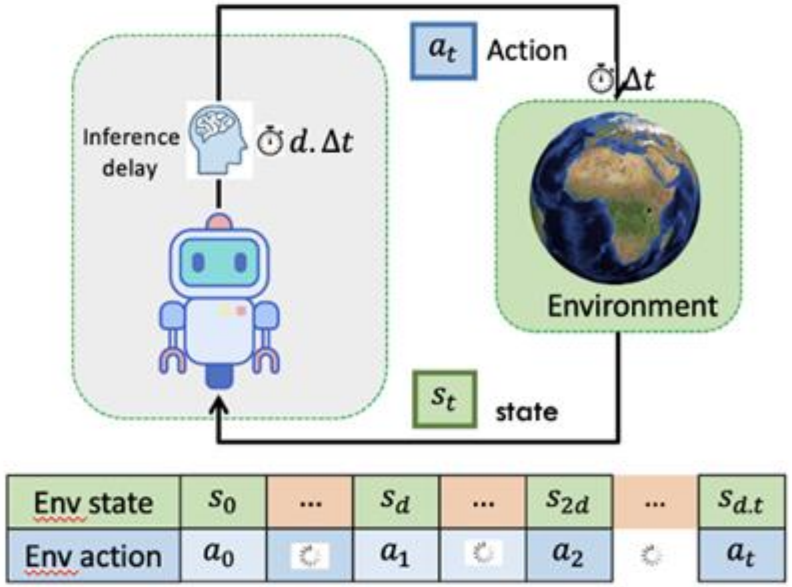


Axis 2 – Physics informed world models PhD Z. El Asri

- Physics-informed world models: RLC’24



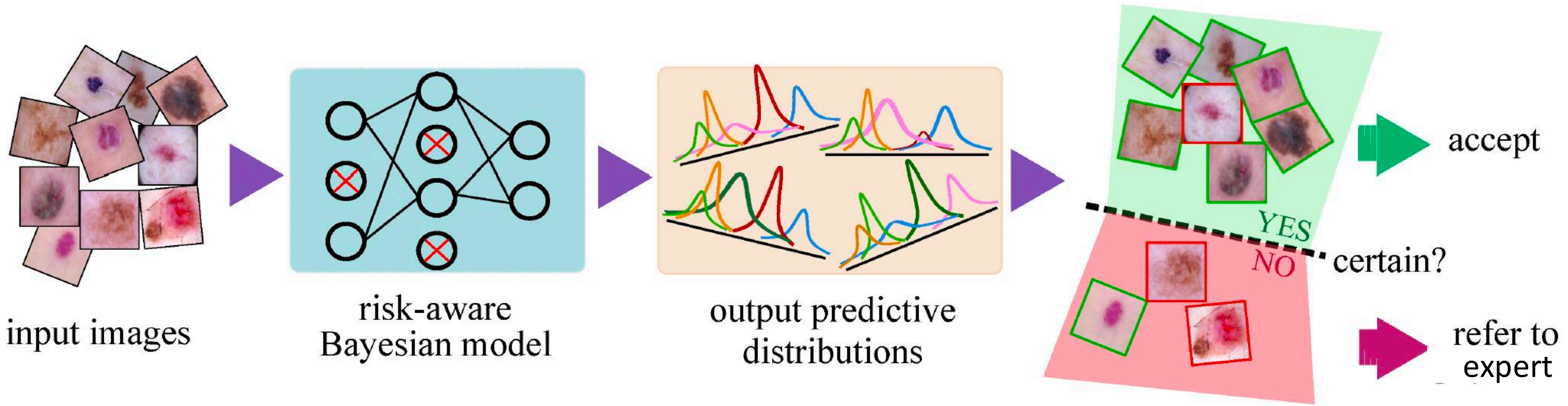
- Direct learning on real robots
- Real-Time Hybrid control with Physics (RT-HCP), IROS’25



Axis 3 - Uncertainty Quantification (UQ)

UQ : Robustness & interactions

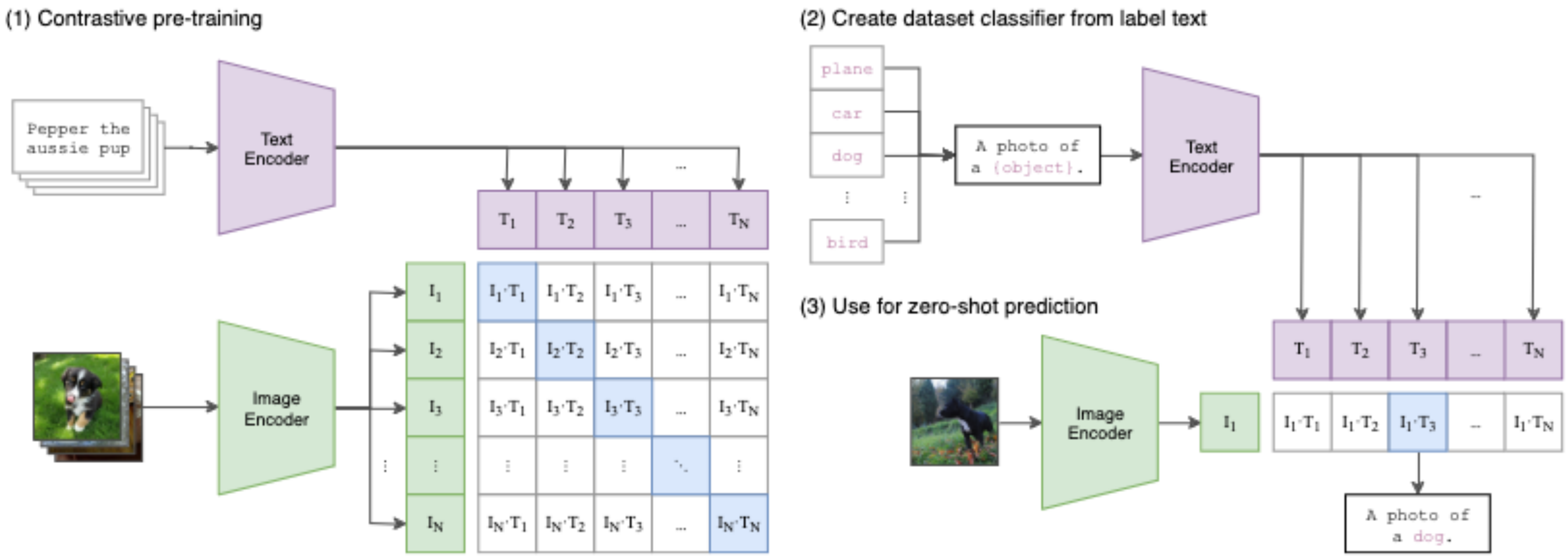
- Detect inability to predict => abstain



=> Trigger surgical team, interact

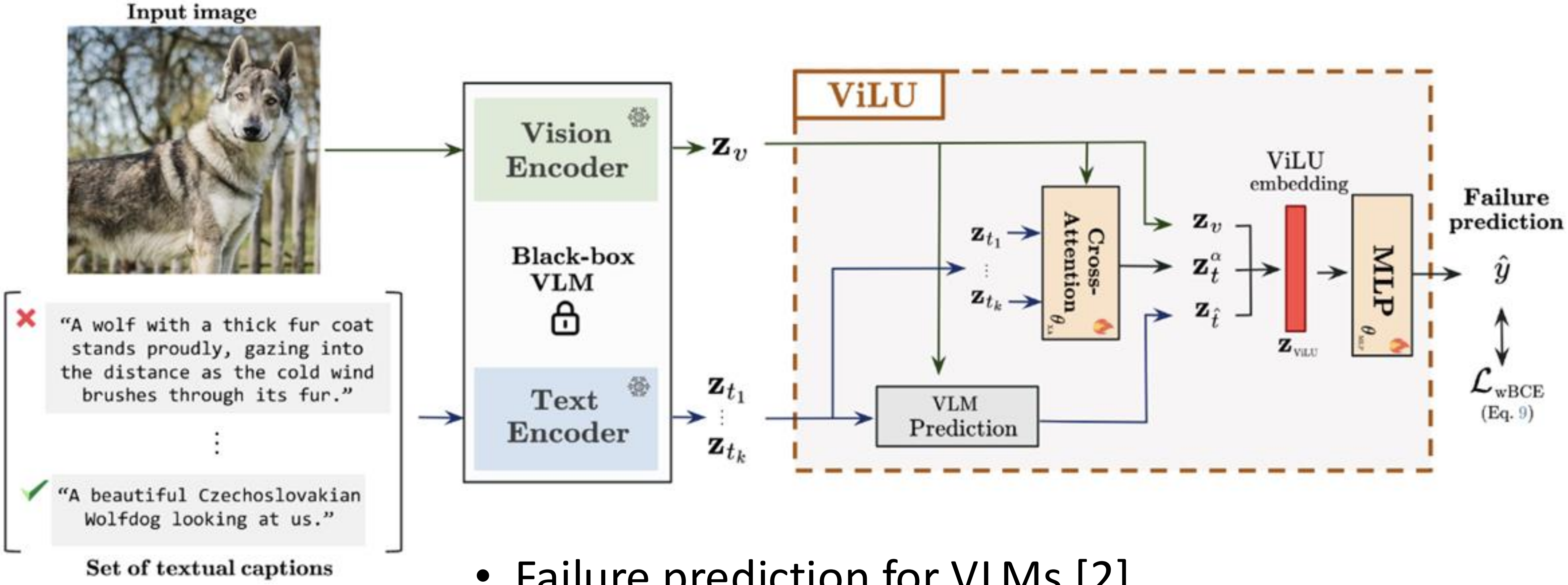
Axis 3 - Vision-Language Models (VLMs)

- Text—image (CLIP) [1]: zero-shot prediction, «foundation model»



[1] Learning Transferable Visual Models From Natural Language Supervision. 1. Radford, J. W. Kim, C. Hallacy, A. Ramesh, G. Goh, S. Agarwal, G. Sastry, A. Askell, P. Mishkin, J. Clark, G. Krueger, I. Sutskever. ICML 2021

Axis 3 - UQ for Vision-Language Models (VLMs)

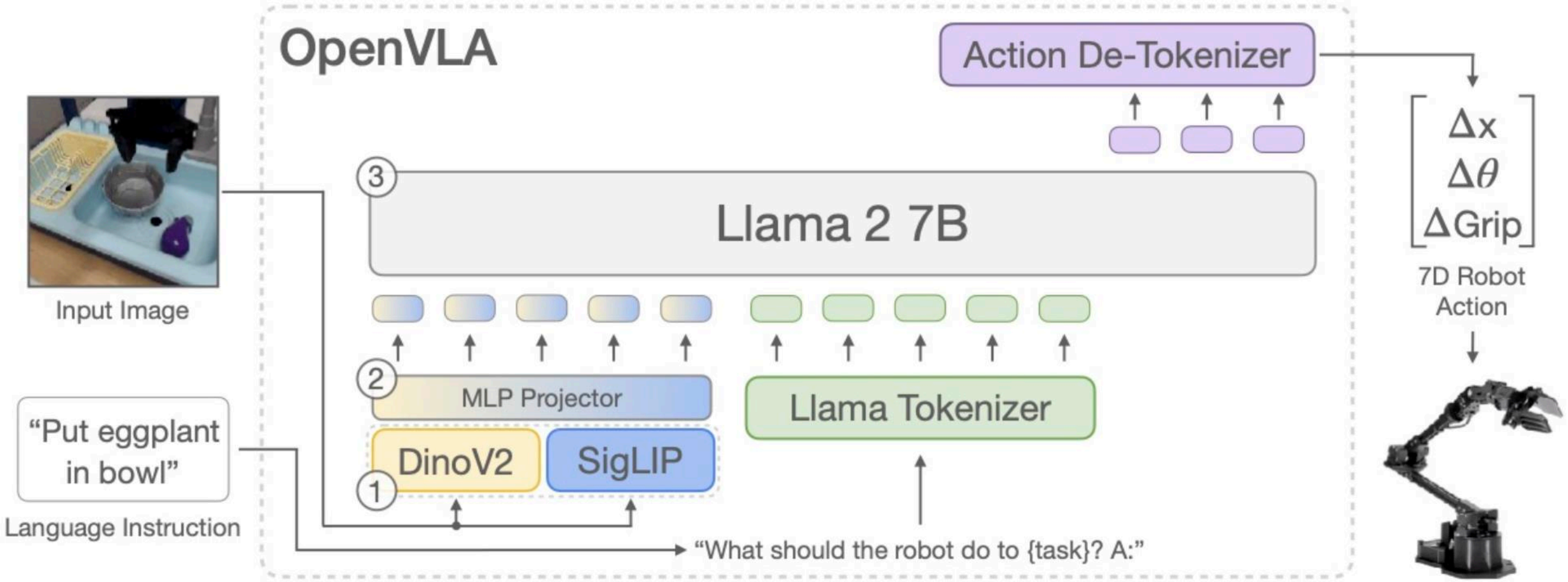


- Failure prediction for VLMs [2]
- Ongoing work: learning a foundation model for UQ

[2] M. Lafon et.al., ViLU: Learning Vision-Language Uncertainties for Failure Prediction. ICCV 2025.

Axis 3 - Foundation models in robotics

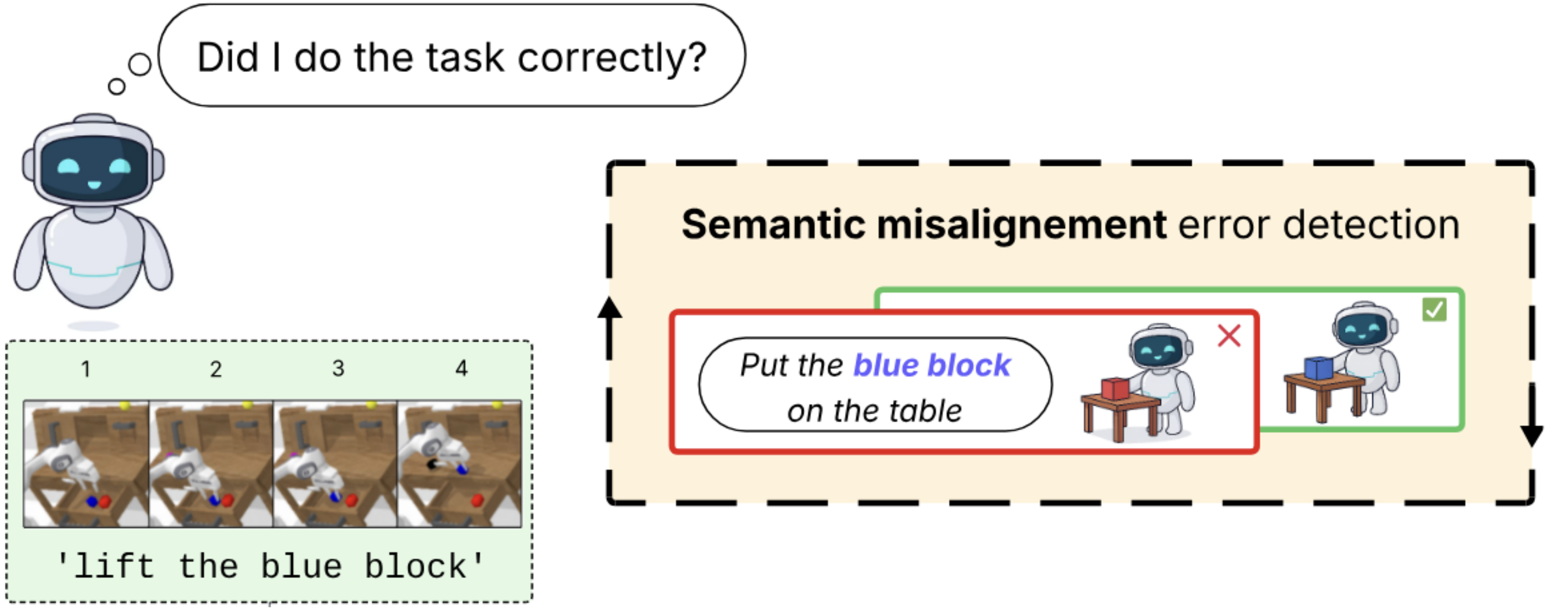
- « Vison Language Action » (VLA), e.g., OpenVLA, SmolVLA [3]
- Learning policies on a wide range of tasks and robot configurations



[3] M. Shukor et.al. SmolVLA: A Vision-Language-Action Model for Affordable and Efficient Robotics. Arxiv, 2025

Axis 3 - Foundation models in robotics

- I-FailSense: Failure precision of VLAs
  - Semantic misalignment



- Use/ Fine-tune VLMs to detect if trajectories fulfil the goal

[4] C. Grislain et.al. I-FailSense: Towards General Robotic Failure Detection with Vision-Language Models. Arxiv, 2025

AI for surgical robotics: conclusion

- Highly transdisciplinary topic: statistics, machine learning, computer science, robotics, surgery
- Challenges:
  - Data availability: collecting data at APHP, work on public data too
  - Robotics: validation on simulators vs real data
    - No simulator in spine surgery
    - Real data limits the experiments on closed loop control
- Opportunities:
  - Highly promising adaptations of recent generative AI models
  - Working on useful and rewarding applications related to healthcare
  - Gathering several capabilities at ISIR: from surgeons to ML researchers

Thank you for your attention

- Questions ?