Towards Connecting Control to Perception:
High-Performance Whole-Body Collision Avoidance Using Control-Compatible Obstacles

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PROBLEM

Collision avoidance is a crucial part of safe manipulation

Requirements (R):

- Self-collision avoidance (see Fig. 1)
  → R1: Whole-body awareness
- Environment collision avoidance (see Fig. 1)
  → R2: Environment awareness (representation)
  → R3: Environment perception (update procedure)
- Flexibility to react safely to unexpected events (see Fig. 2)
  → R4: Real-time capability
- Adaptability, e.g., for keeping the ability to manipulate and avoid collisions with grasped objects
  → R5: Connection to a knowledge base

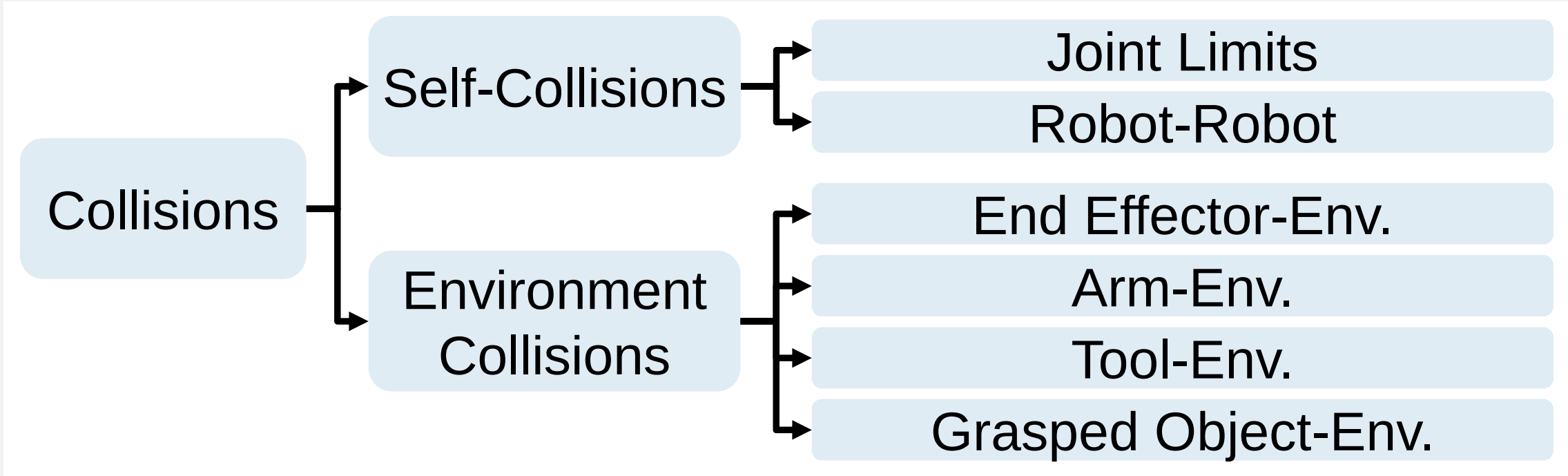

Fig. 1: The taxonomy of the collision types that must be considered in collision avoidance for safe manipulation. Collision types can be divided into two groups: (1) self-collisions and (2) environment (env.) collisions.

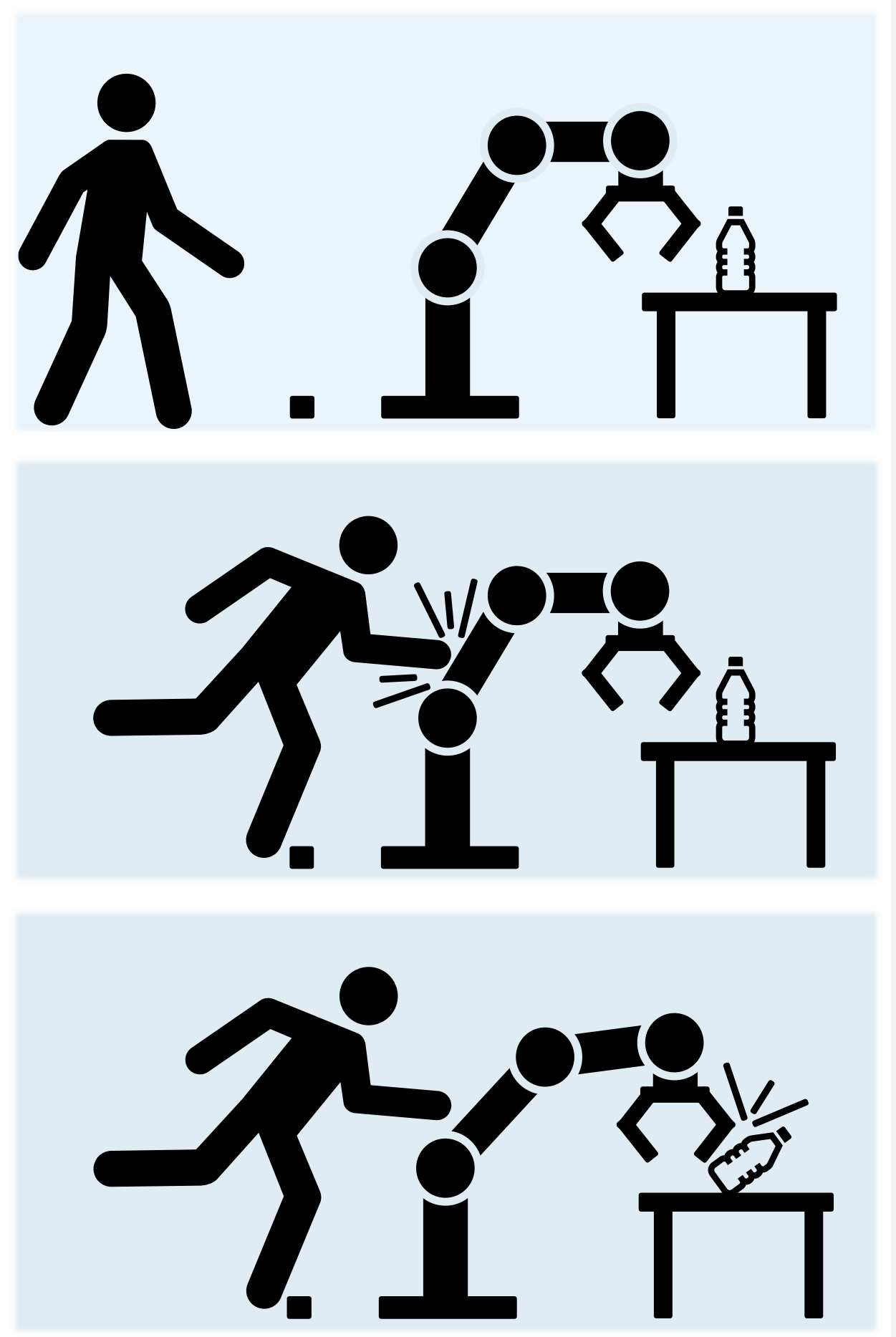

Fig. 2: A robot without a real-time environment-aware collision avoidance control is unable to react safely to unexpected events such as an unavoidable human-robot collision. This may lead to further unwanted events, as shown in this figure.

APPROACH

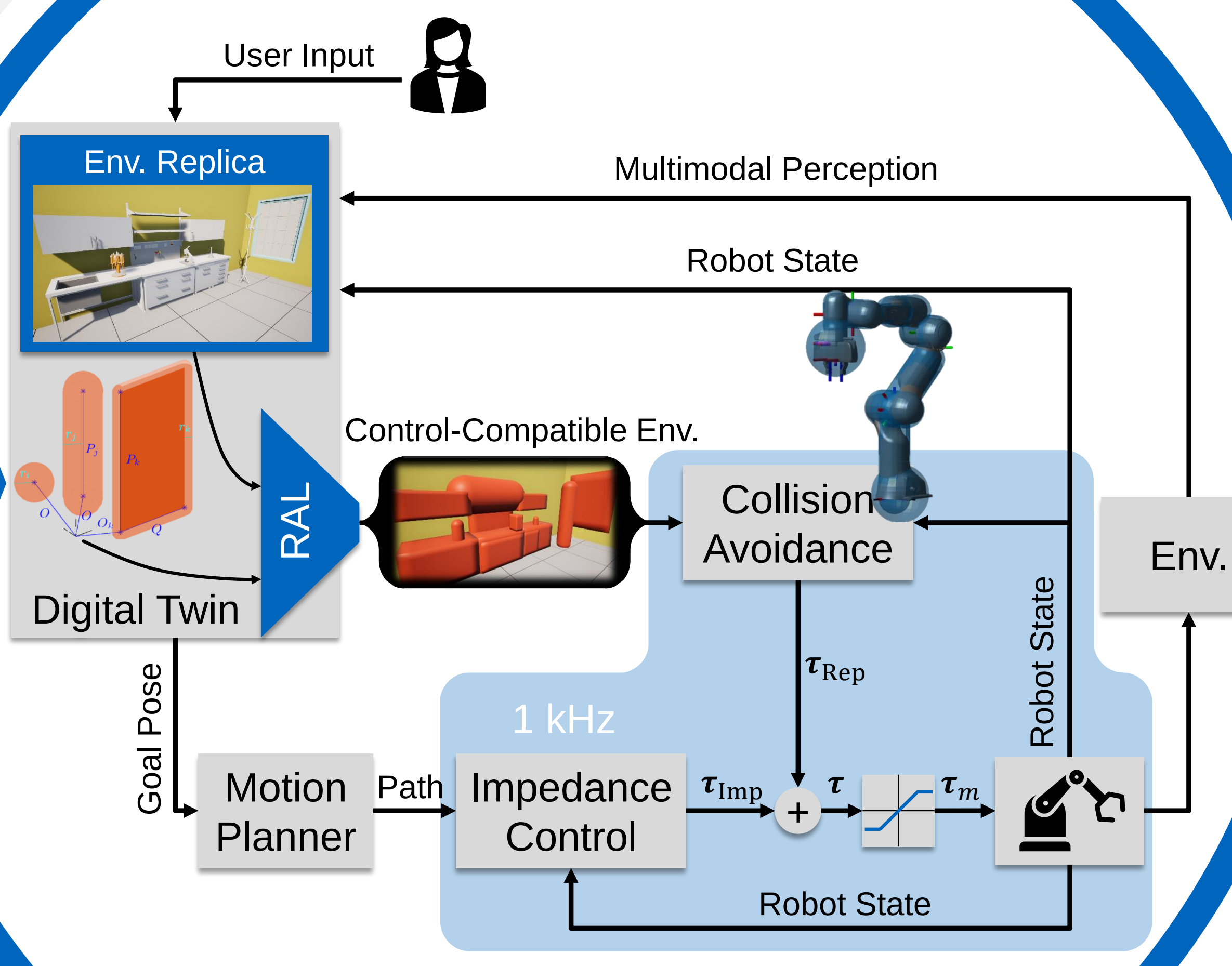

Fig. 3: Visualization of our control loop connecting control to perception. The 1 kHz Artificial Potential Filed (APF)-based collision avoidance control allows for flexible and safe reactions to unexpected events. Its connection to the digital twin through our Replica Abstraction Layer (RAL) adds environment (env.)-awareness and enables additional adaptability to, e.g., be able to manipulate while avoiding collisions or consider grasped objects in the collision avoidance control.

EXPERIMENTAL RESULTS / PIPELINE

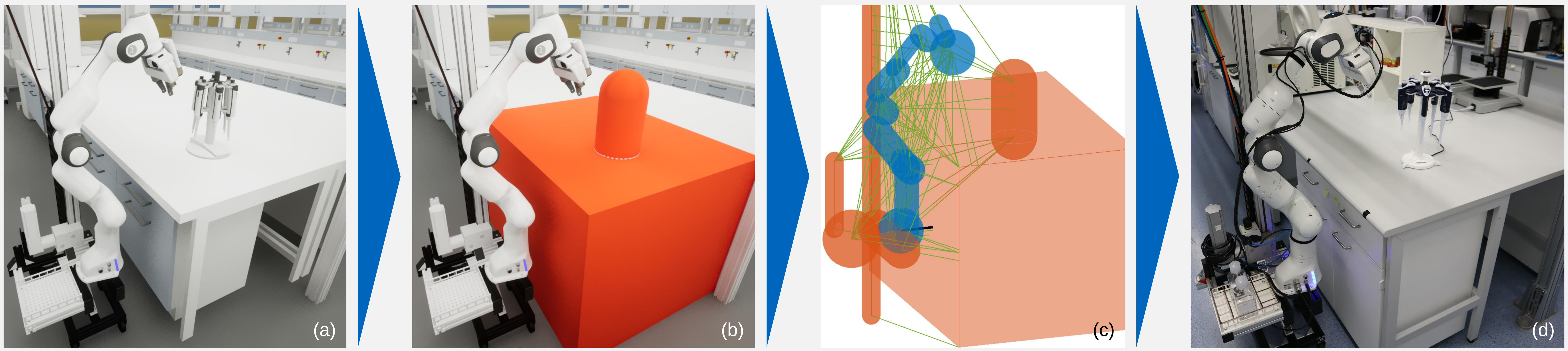

Fig. 4: The visualization of our pipeline for connecting control to perception, captured during the experiments. (a) shows the environment replica stored in the digital twin and constantly updated through a multimodal sensory environment perception. Based on this, our new Replica Abstraction Layer (RAL) displayed in (b) creates control-compatible environment primitives for the currently reachable objects. The environment primitives are complemented by those of the robot in 1 kHz real time by our collision avoidance control shown in (c). It then calculates distances between all possible collision pairs (green lines) and determines virtual Cartesian repulsive forces along the connecting distance lines for those (black lines) below a certain threshold (we used 6 cm). The Cartesian forces are transformed into joint torques τ_{Rep}, which are then applied to the real-world robot in (d).

DISCUSSION AND FUTURE WORK

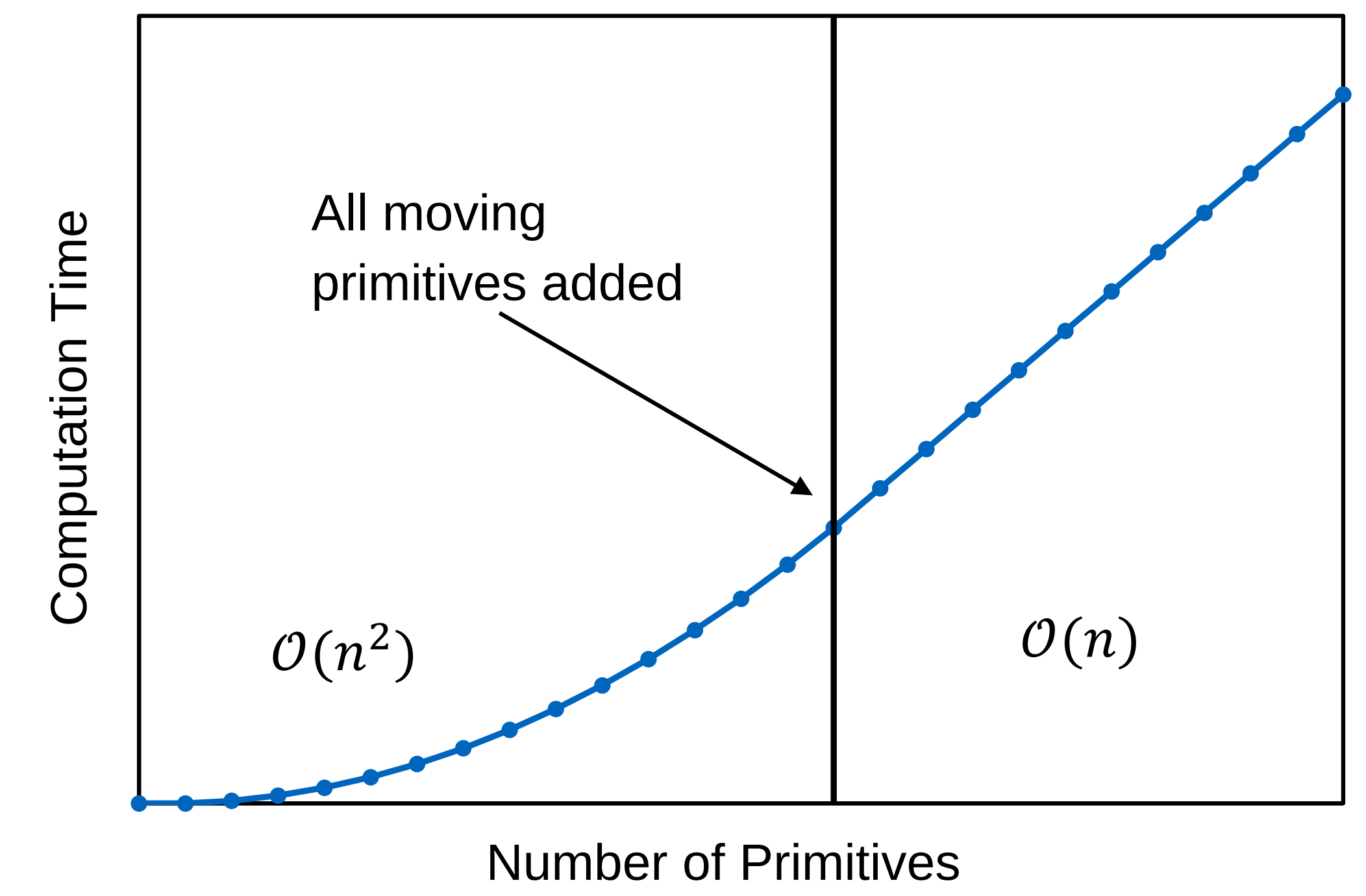

Fig. 5: Qualitative graph showing how the algorithm's computation time scales when adding more primitives. The time complexity is quadratic in the beginning when describing the moving/robot primitives because all moving primitives can collide with each other. After describing the robot, only the environment can become more and more complex. The environment primitives, however, can only collide with those from the robot and not with each other, which is why they cause a linear time complexity only.

Discussion on computation times:

- Average **computation time of 7.45 µs** in the scenario of Fig. 4c
  — 4 spheres, 12 capsules, and 3 planes result in 126 collision pairs
- Computation time **scales with the number of primitives** (Fig. 5)
  — $\mathcal{O}(n^2)$ until all moving primitives are added
  — $\mathcal{O}(n)$ towards infinity

Limitations and future work:

- No globally optimized motions
- Local minima may exist that can lead to convergence issues

→ **Combine with a Cartesian space collision-free motion planning** (Table I)

TABLE I: Decision matrix showing why an APF-based environment-aware collision avoidance control is useful and with what of other collision avoidance methods our solution can be complemented to achieve better global results.

Method / Feature	CBF-based self-collision avoidance control	CBF-based env.-aware collision avoidance control	APF-based self-collision avoidance control	APF-based env.-aware collision avoidance control	Cartesian space collision-free motion planning	Joint space collision-free motion planning
Whole-body collision avoidance	✓	✓	✓	✓	×	✓
Real-time capability	×	×	✓	✓	×	×
Handling of unexpected scenarios	×	×	×	✓	×	×
Globally optimized paths	×	×	×	×	✓	×
Local minima-free and convergent	✓	✓	×	×	✓	✓

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Glossary	
Env.	Environment
RAL	Replica Abstraction Layer
APF	Artificial Potential Field
CBF	Control Barrier Function