

MATER: Mutually Aware Framework for Teleoperated-robot with Extended Reality

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XR Teleoperation

What is XR Teleoperation?

- User operates a remote robot with an Extended Reality (XR) device
- User views robot state in a 3D space and controls with direct user motion – like Avatar!

User view



Remote robot



XR Teleoperation use cases

- Operate robot in hazardous environment
- Remote control, surgery, automation

Fire fighter uses XR Teleoperation*



Da Vinci Robotic Surgery**

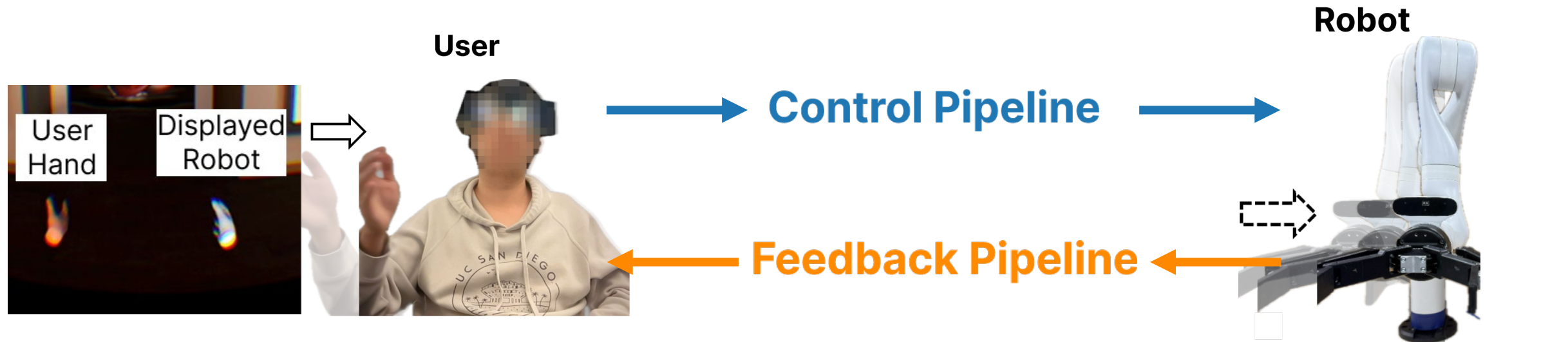


* ChatGPT 5.5, Fire-fighter operating robot with XR (Generated)

** OHC, What is Da Vinci Robotic Surgery <https://ohcare.com/what-is-da-vinci-robotic-surgery/>

XR Teleoperation pipeline

- **Control Pipeline:** User motion is sampled by XR sensors and transmitted to robot for control
- **Feedback Pipeline:** Robot feeds back real-time pose and environment data for user to view and conduct subsequent motion



XR Teleoperation Challenges

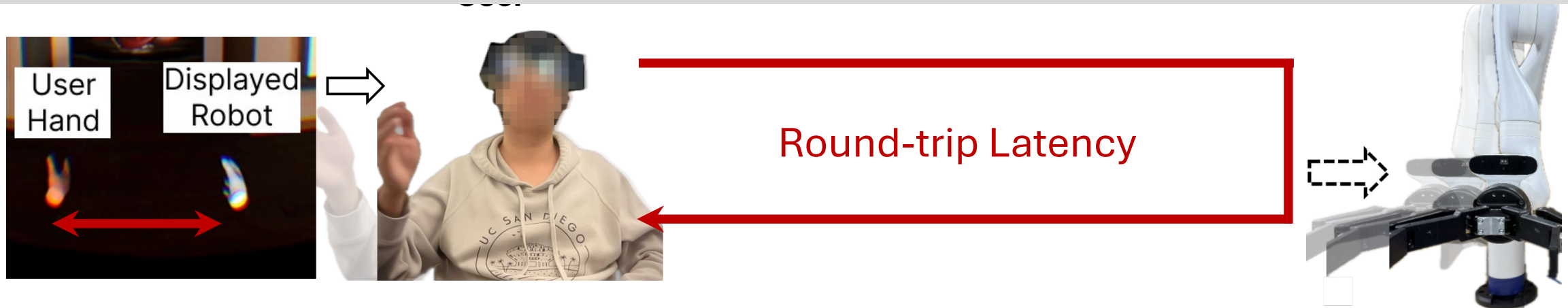
- **Communication Latency:** User always experience one round-trip latency
- **Teleoperation Accuracy:** User always observes robot lags behind and has to stop constantly for robot to catch up – **teleoperation error**



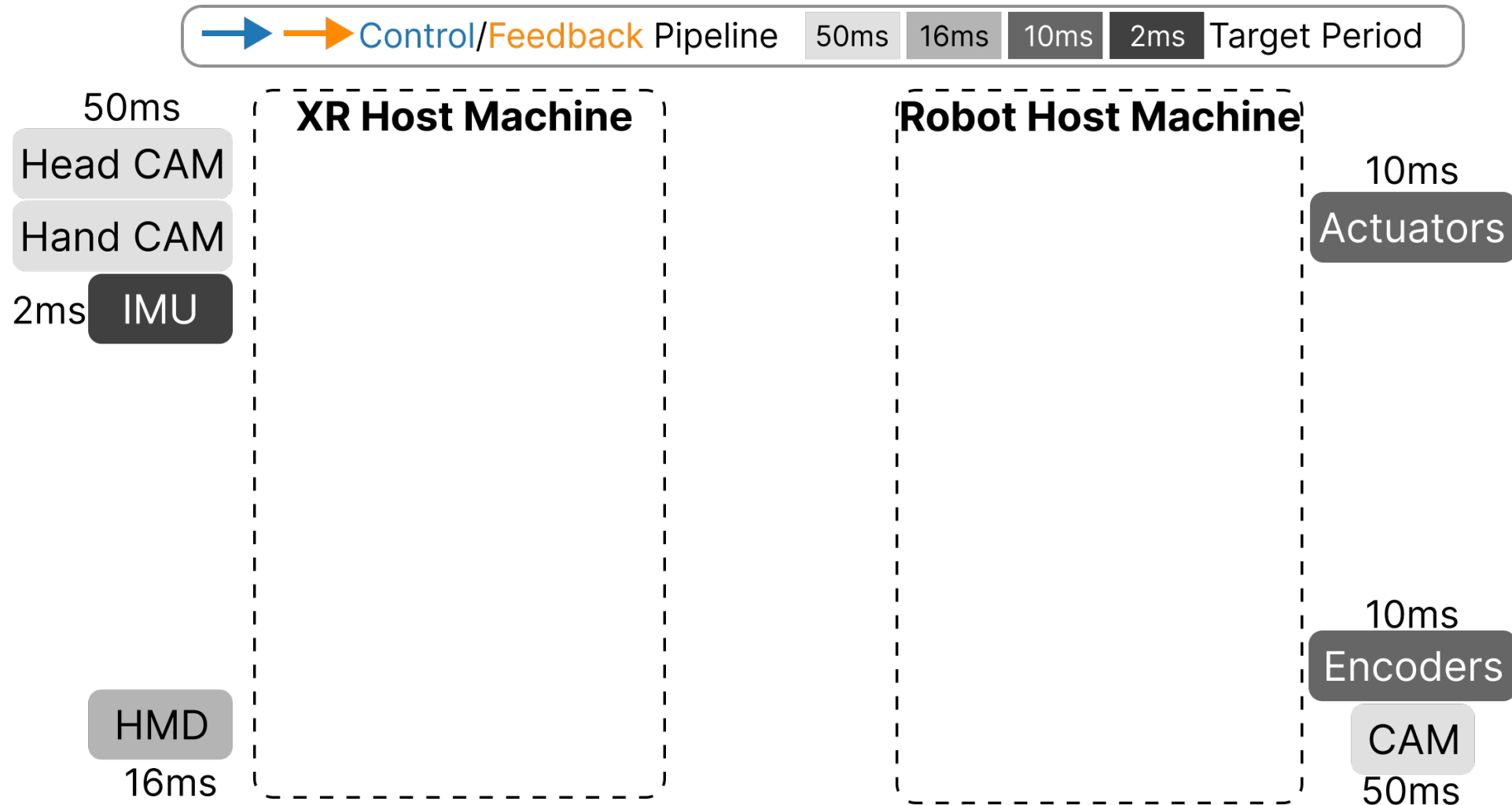
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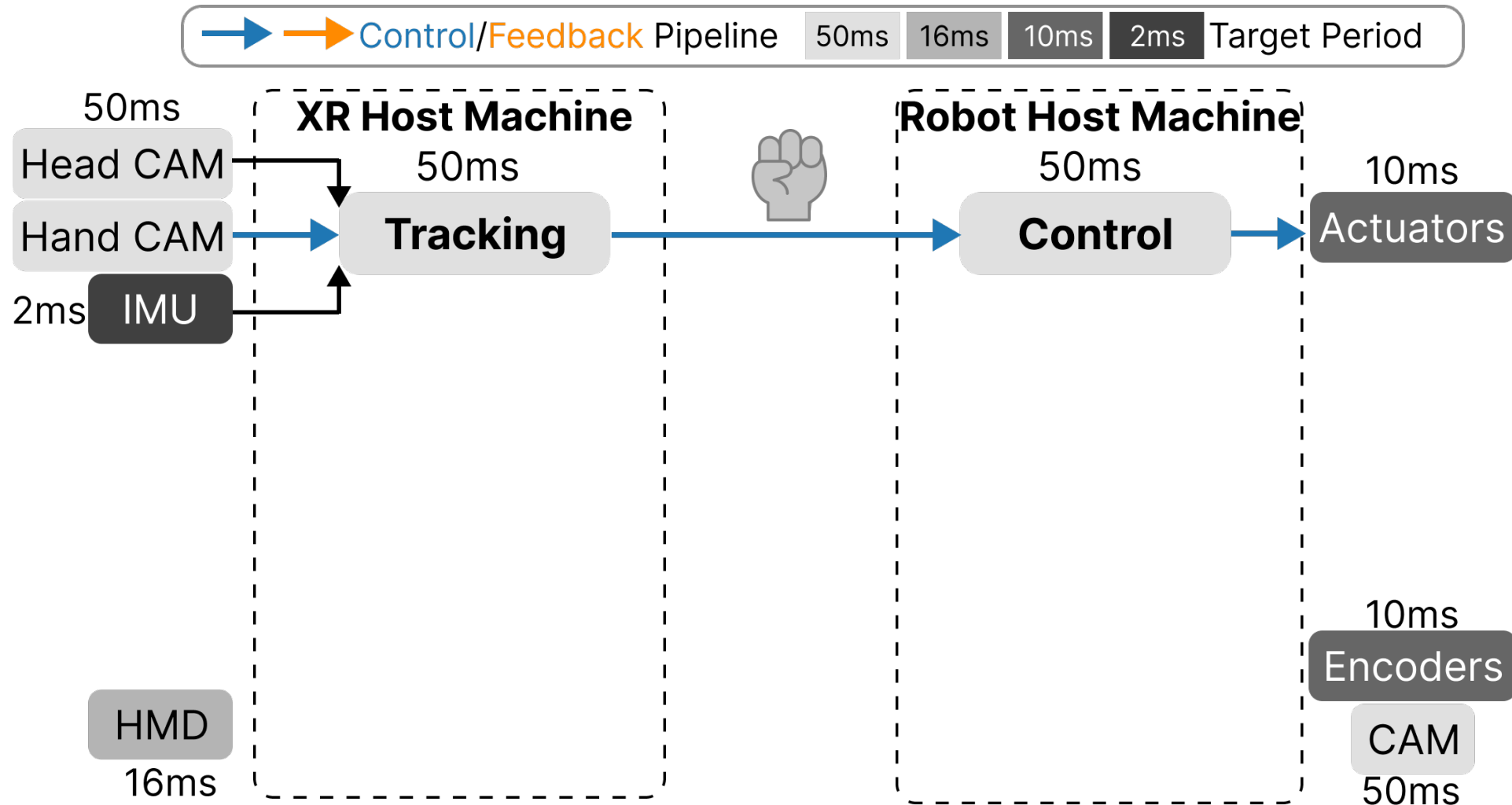
Let's figure out why in the system!



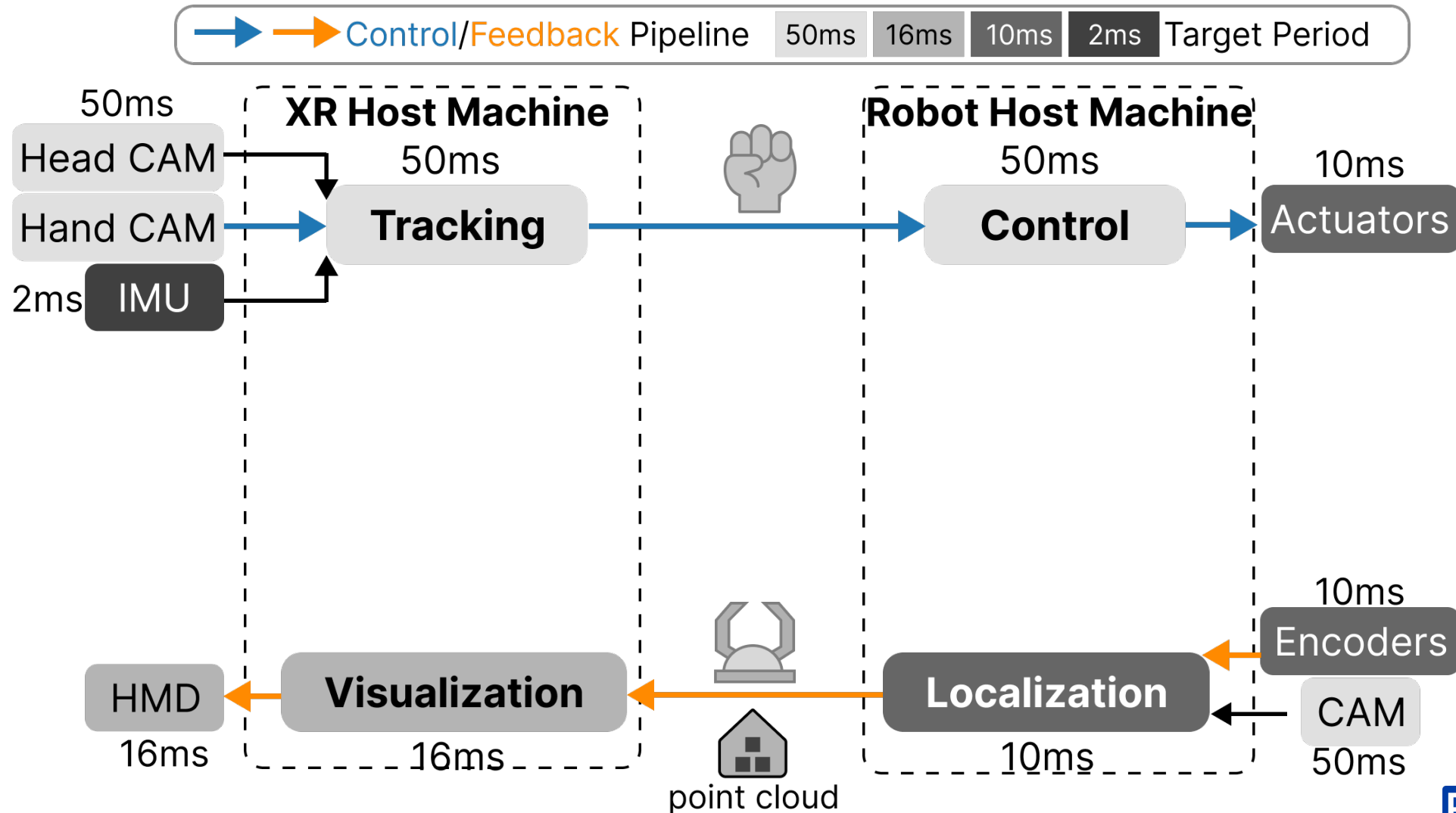
XR Teleoperation System Framework



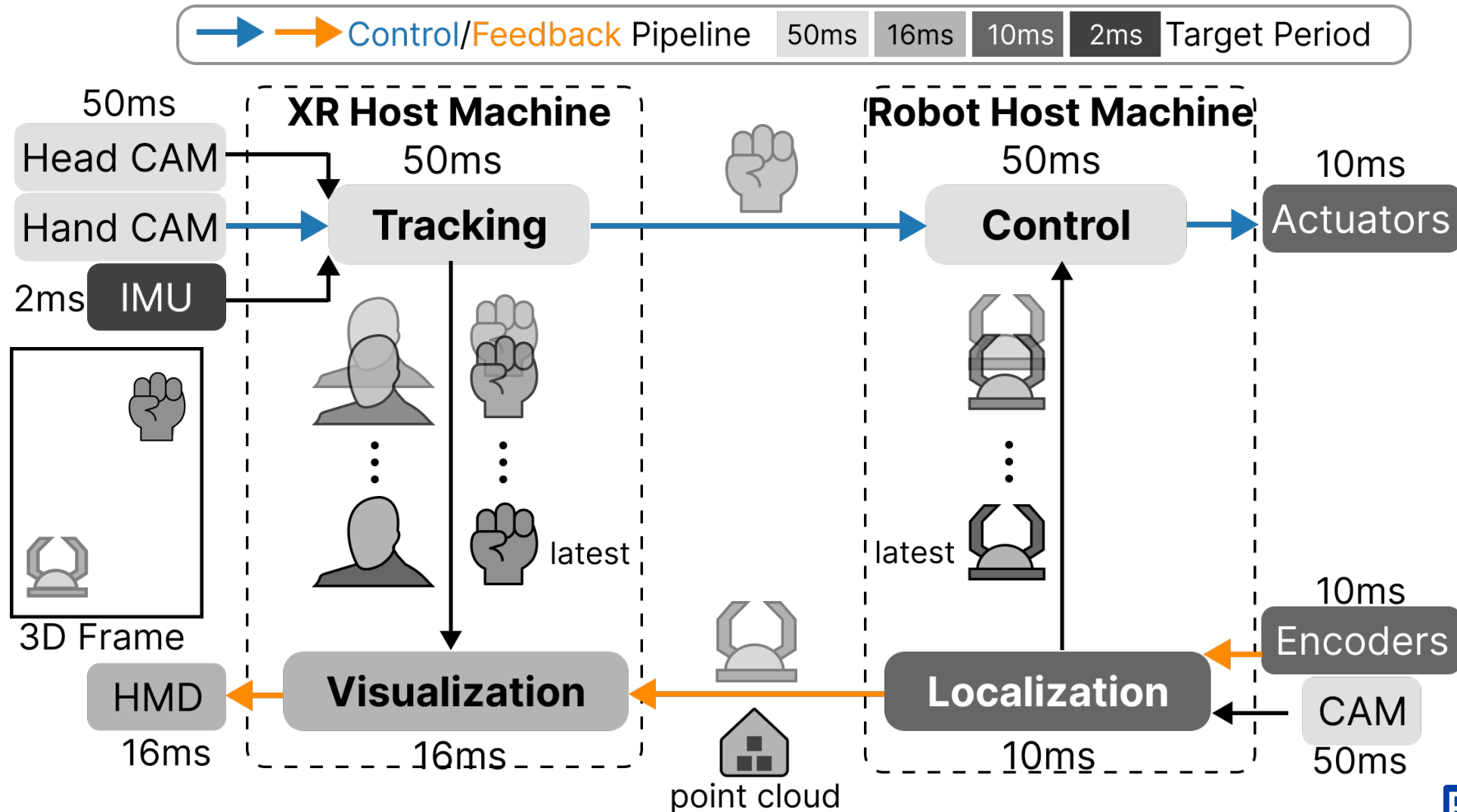
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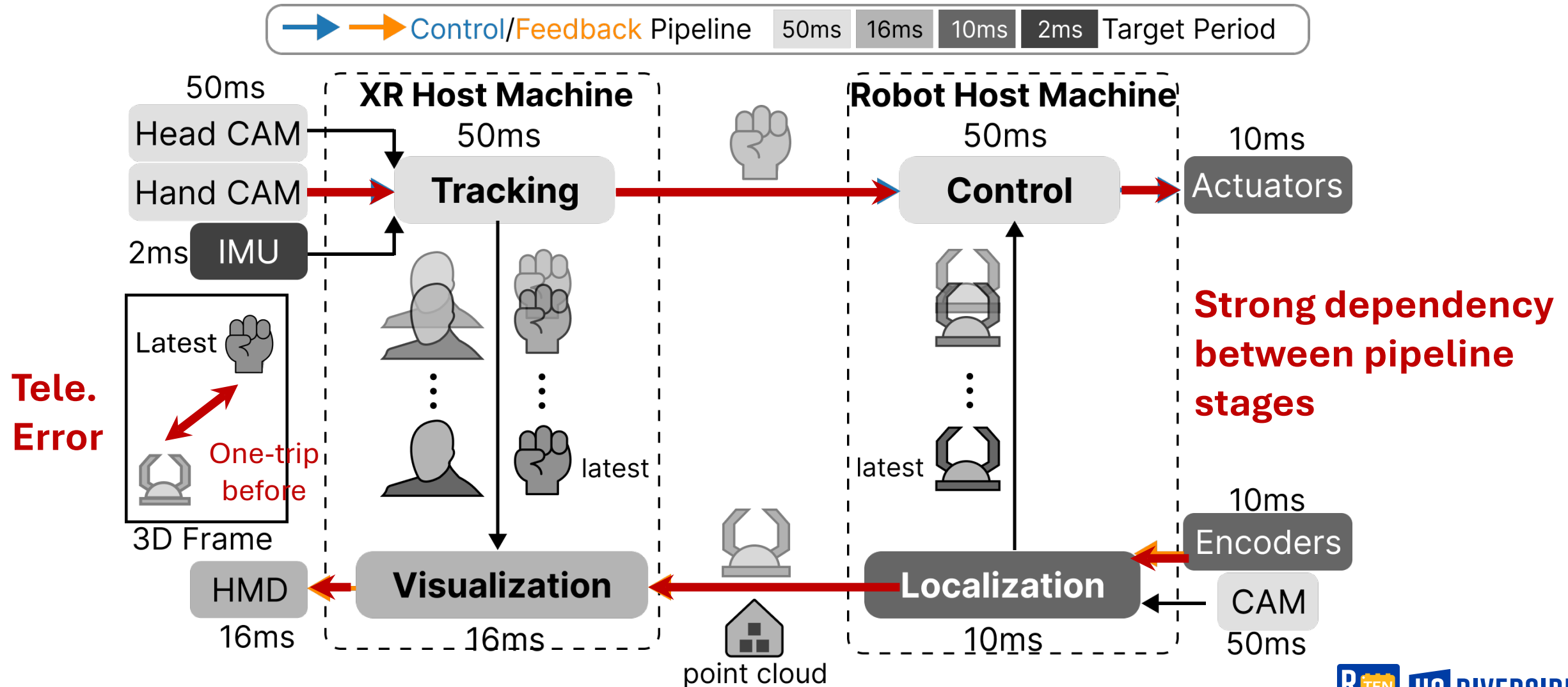
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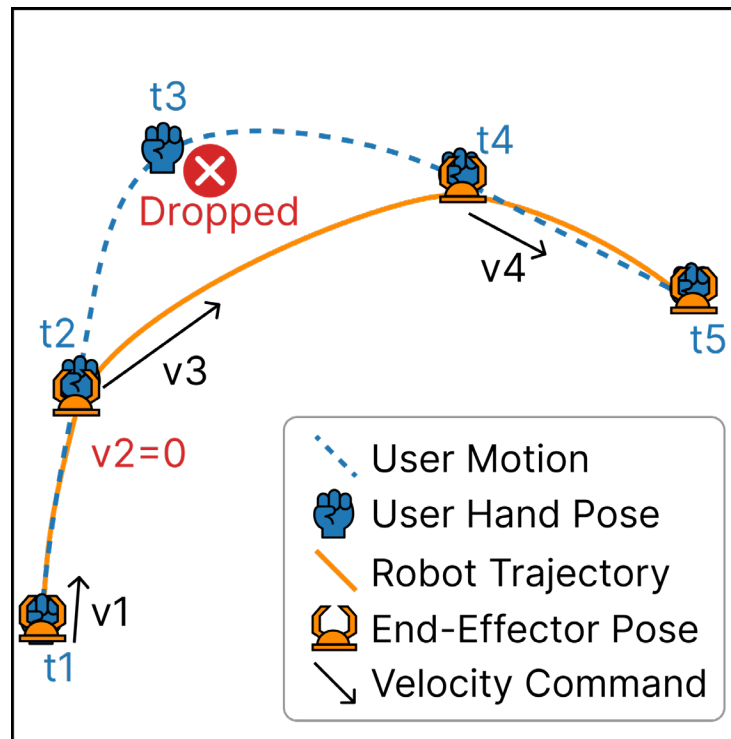
XR Teleoperation System Framework



However, it is hard to solve the problem...

C1: Network-dependent Teleoperation Performance

- Pose Drop: robot skips t3 and produces irrecoverable deviation

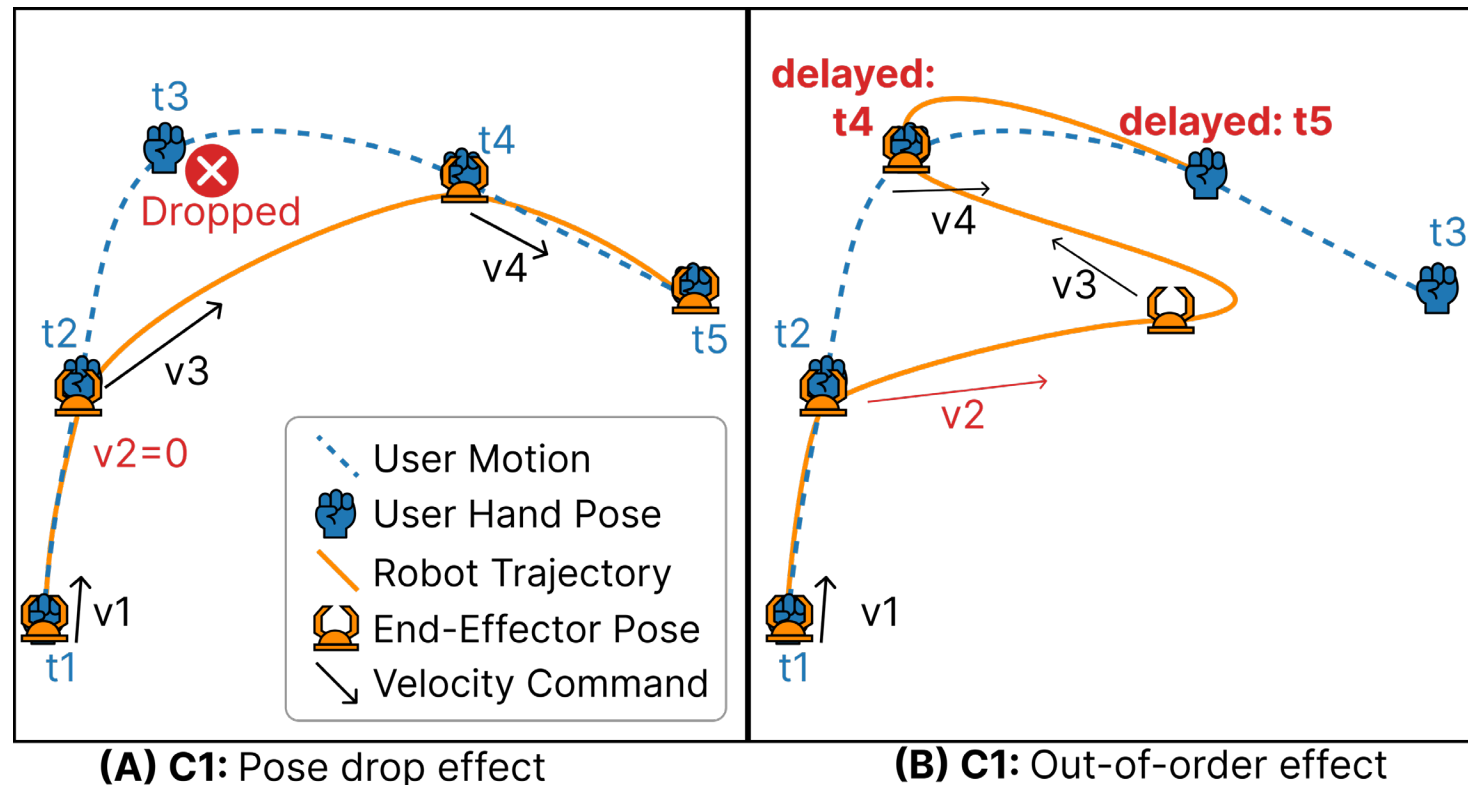


(A) C1: Pose drop effect

However, it is hard to solve the problem...

C1: Network-dependent Teleoperation Performance

- Pose Drop: robot skips t3 and produces irrecoverable deviation
- Out-of-order arrival: robot prematurely executes t3 before receiving the correct t4



However, it is hard to solve the problem...

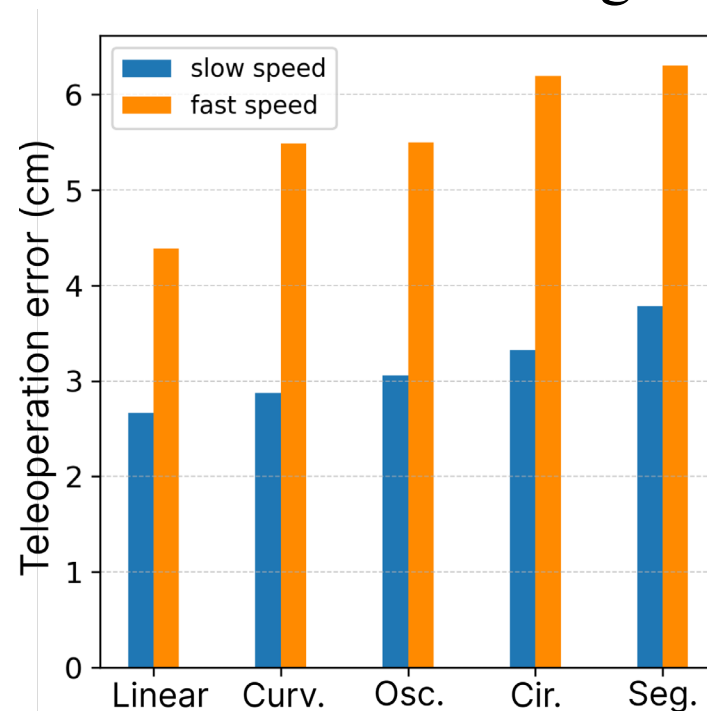
C2: Motion-driven Teleoperation Accuracy

- Higher speeds increase Tele. Error: distance between the displayed and remote robot naturally grows when user speed increases

However, it is hard to solve the problem...

C2: Motion-driven Teleoperation Accuracy

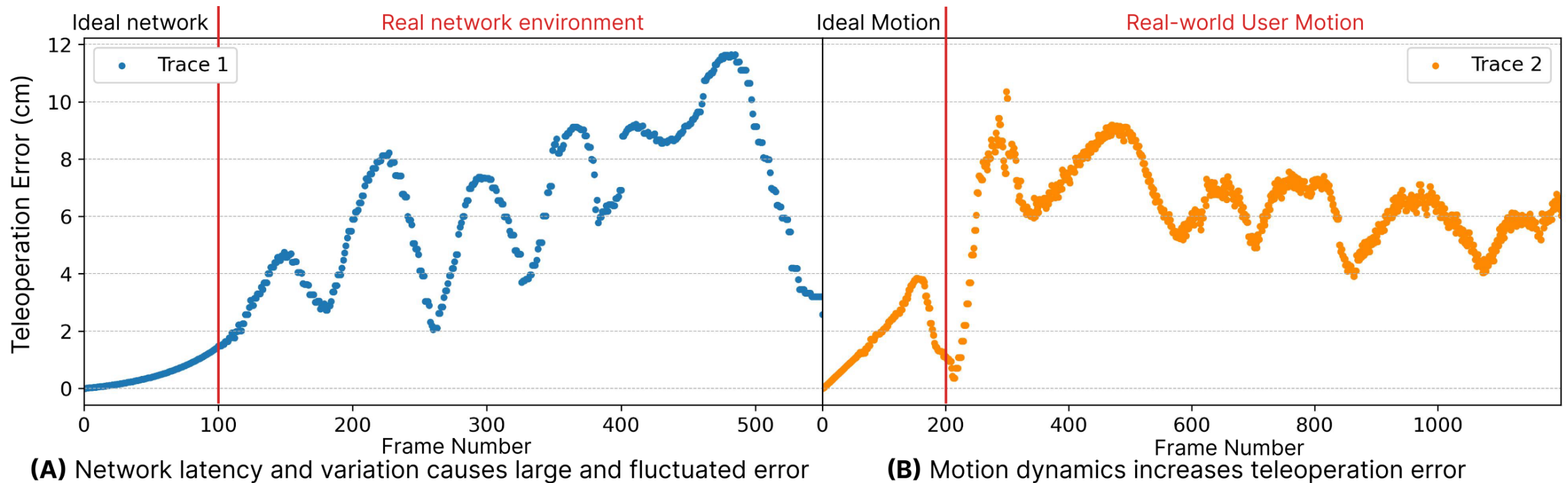
- Higher speeds increase Tele. Error: distance between the displayed and remote robot naturally grows when user speed increases
- High-curvature motions increase Tele. Error: higher-curvature motions amplify the impact of delay



(C) C2: Motion effect on MATER

Therefore, in real-world deployment

- Error increases to over 10 cm due to real network fluctuation and motion dynamics



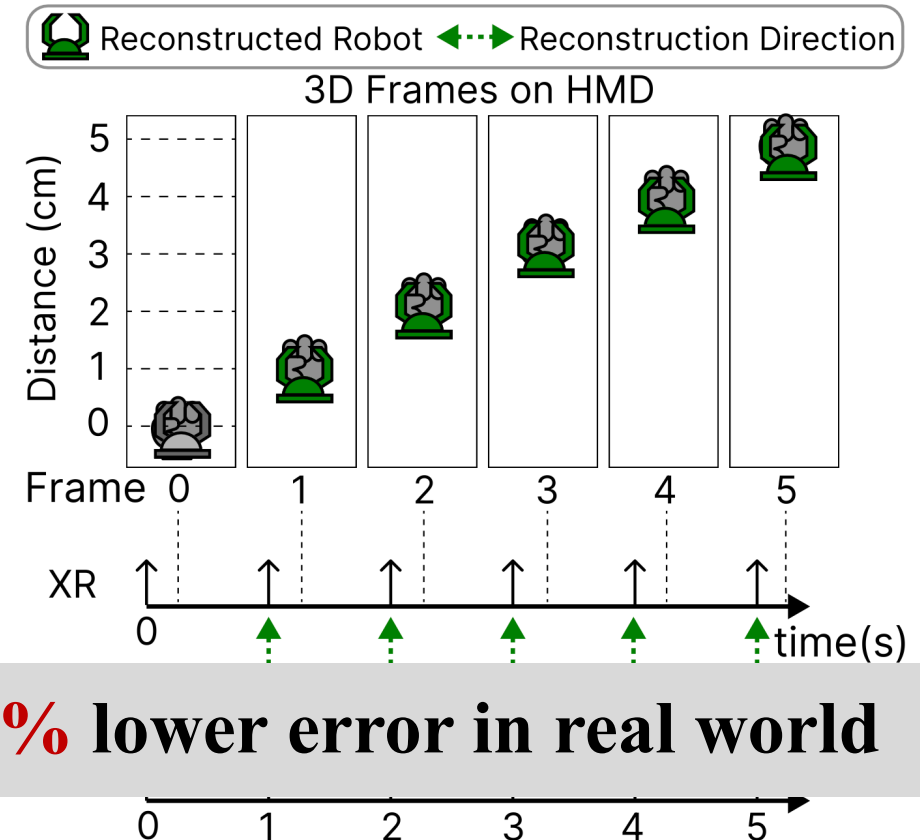
Our Solution: MATER

Root cause: Synchronous execution architecture

- Both XR and robot must wait for network updates to maintain state consistency
→ Vulnerable to network latency (C1) and motion dynamics (C2)

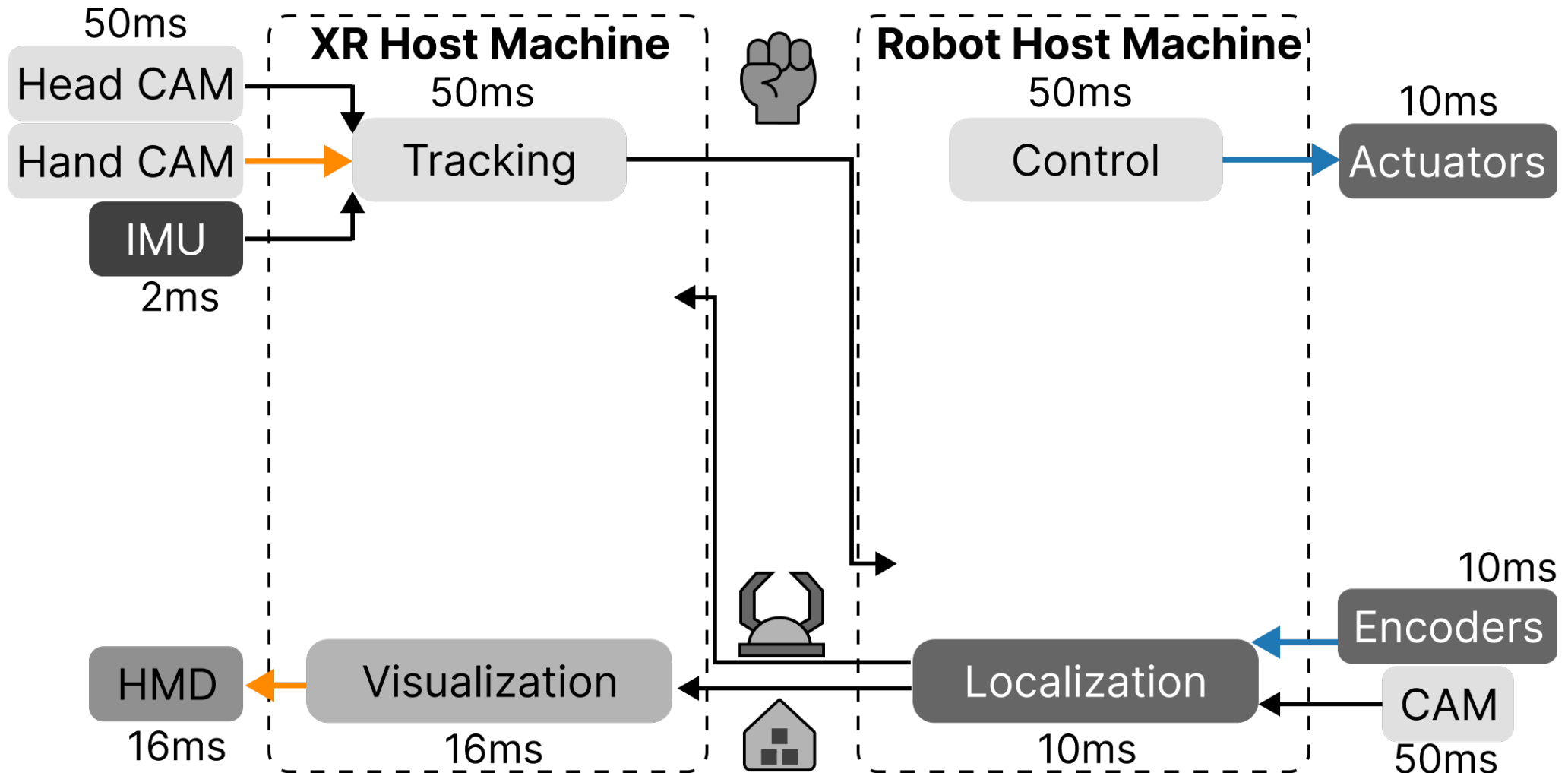
Key insight: Mutually-aware paradigm

- Decouple execution from network dependency by locally reconstructing its counterpart's states
- Three architectural shifts
 - Bidirectional Reconstruction of Time-Shifted States
 - Asynchronous Global & Synchronous Local Execution
 - Control/Data Plane Separation

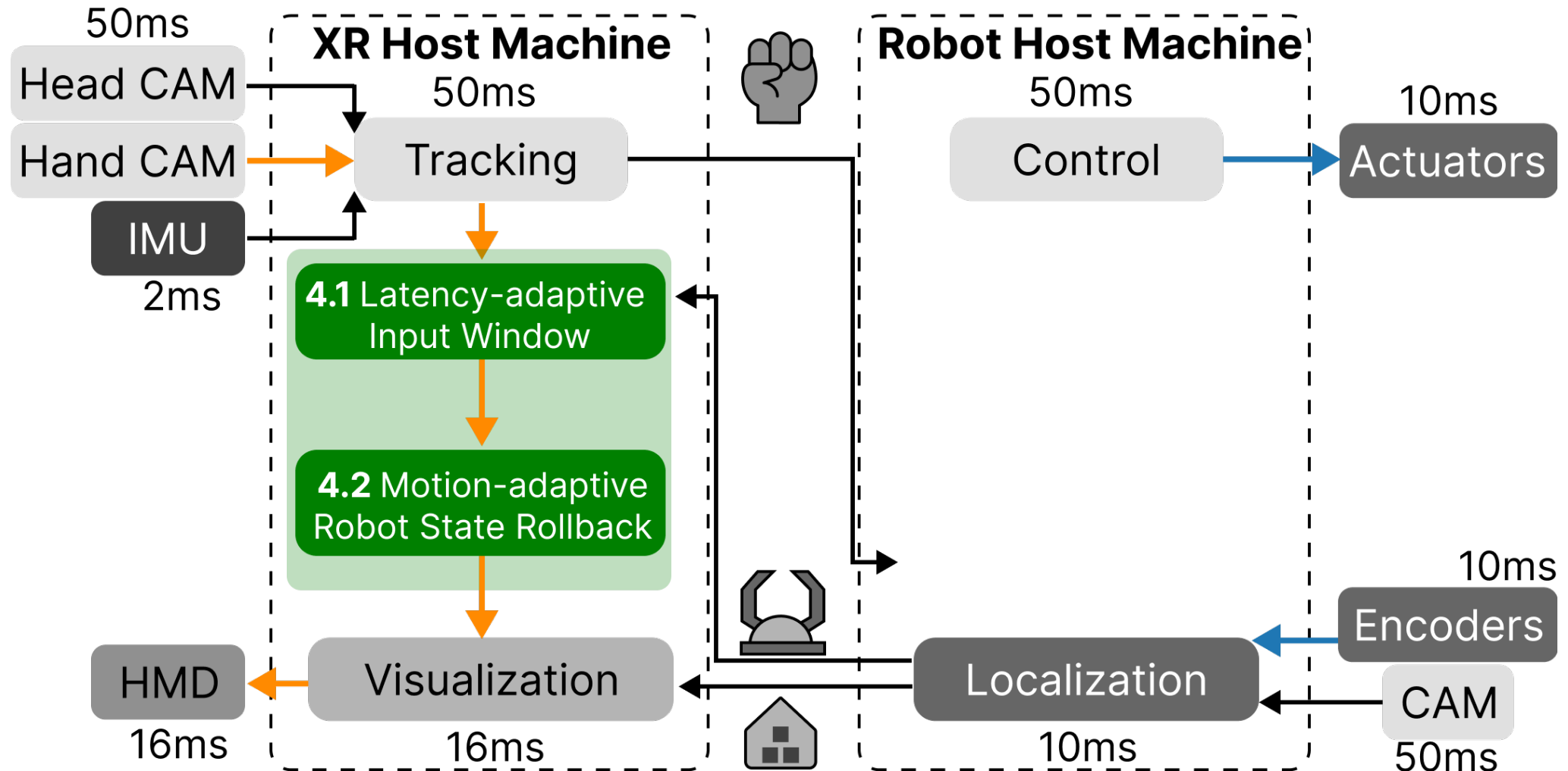


Up to **37.7%** faster mission completion & **57.2%** lower error in real world

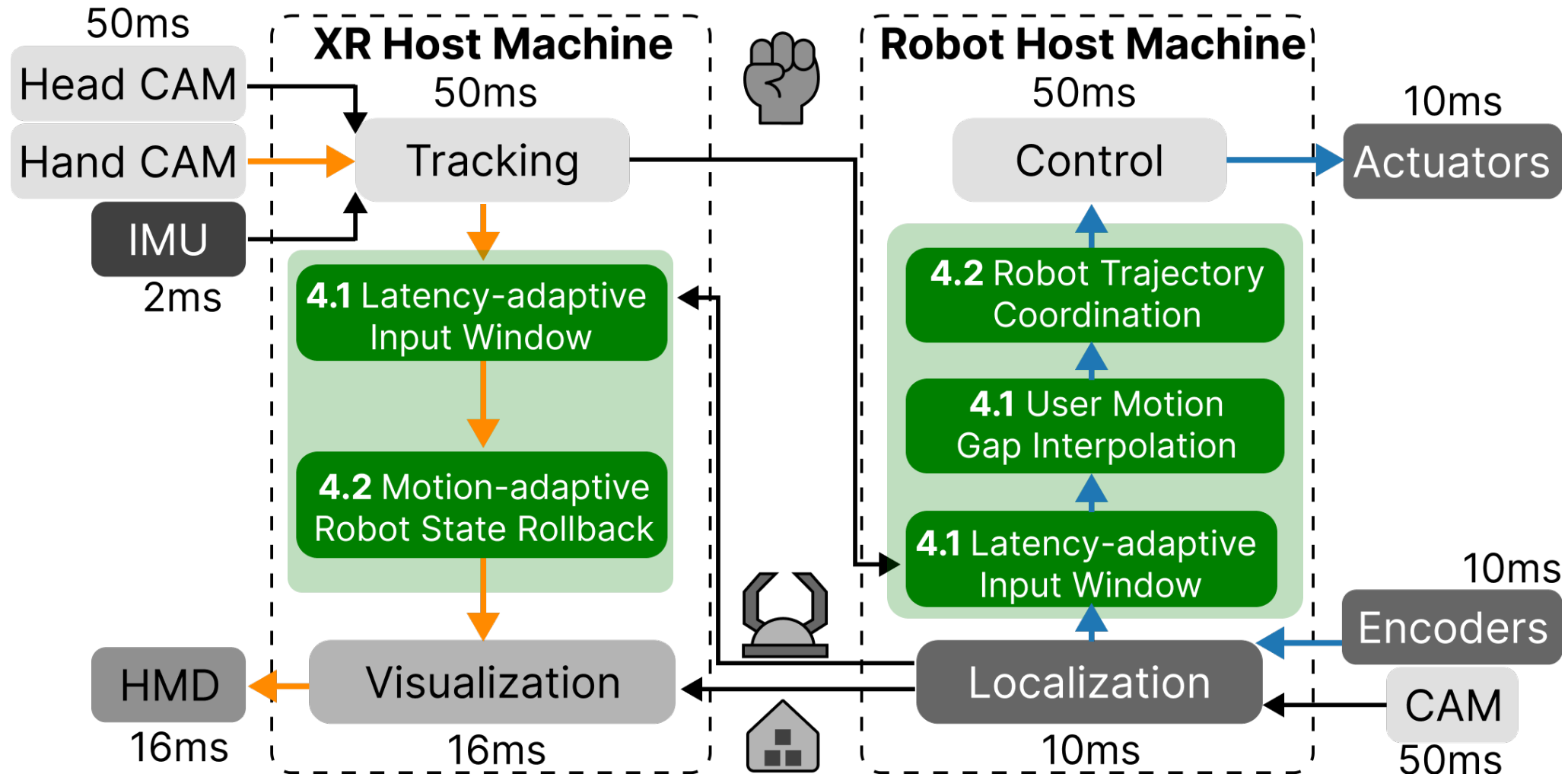
MATER Framework Overview



MATER Framework Overview



MATER Framework Overview



Bidirectional Reconstruction: Network Fluctuations (C1)

Problem: Reconstruction relies on poses sent over the network → latency, drops, and out-of-order arrivals

Latency-adaptive Input Window

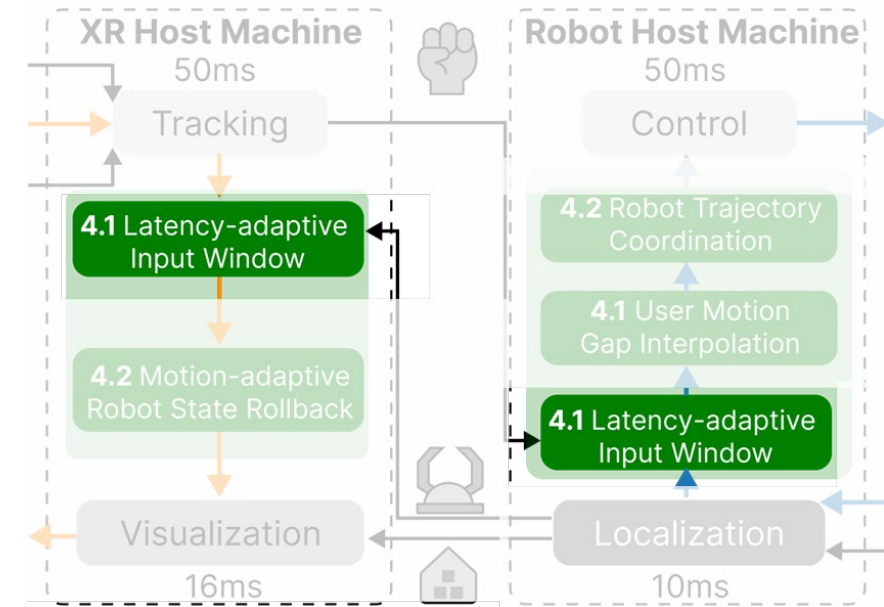
- Adapts input window to the most recently round-trip latency and the robot encoder period

$$k_t^* = \left\lceil \frac{\Delta t_t}{\tau} \right\rceil, \quad k_t = \min \left\{ \max \{ k_{\min}, k_t^* \}, k_{\max} \right\}$$

Round-trip latency

User selected range

Robot encoder period

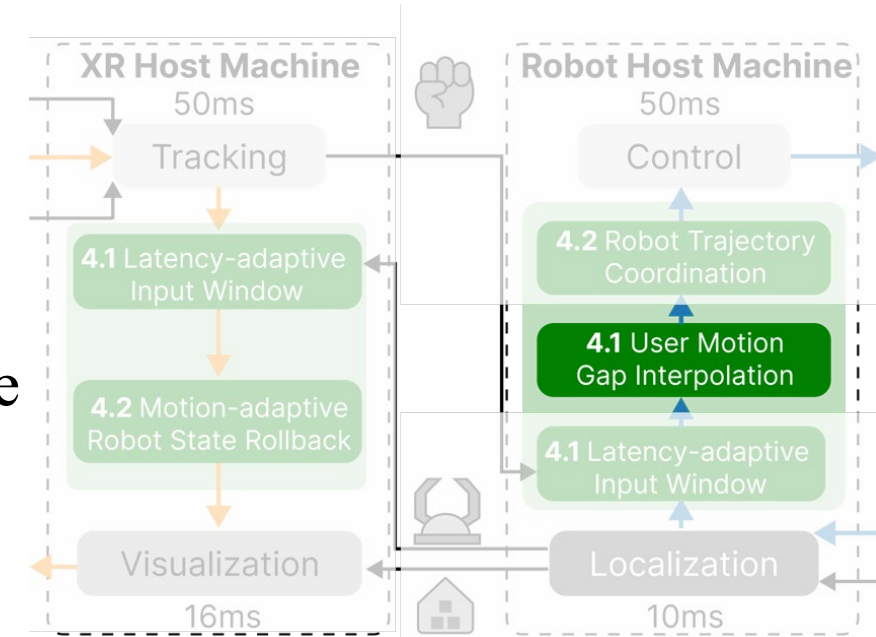
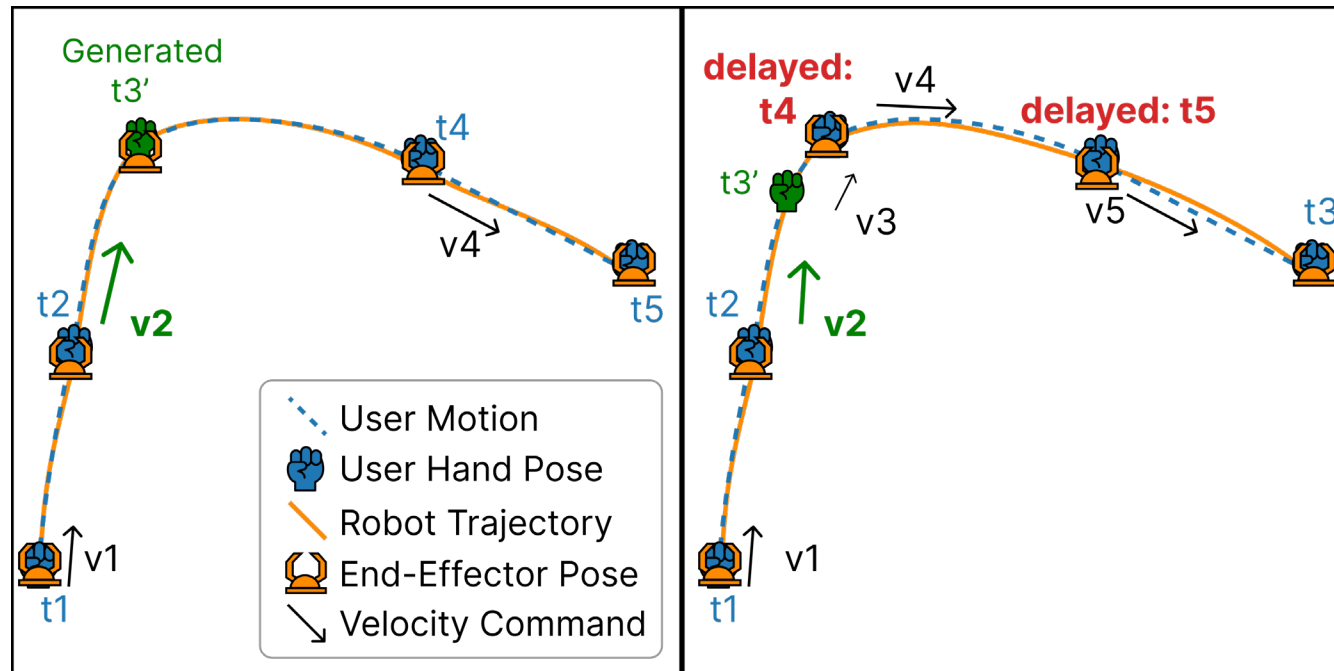


Bidirectional Reconstruction: Network Fluctuations (C1)

Problem: Robot still needs a continuous target when user poses drop or arrive late

User Motion Gap Interpolation

- Detects gap & interpolates waypoints toward next pose



Bidirectional Reconstruction: Motion Dynamics (C2)

Problem: Reconstruction accuracy drops under fast/high-curvature motion, and a wrong robot state can go unnoticed by the user

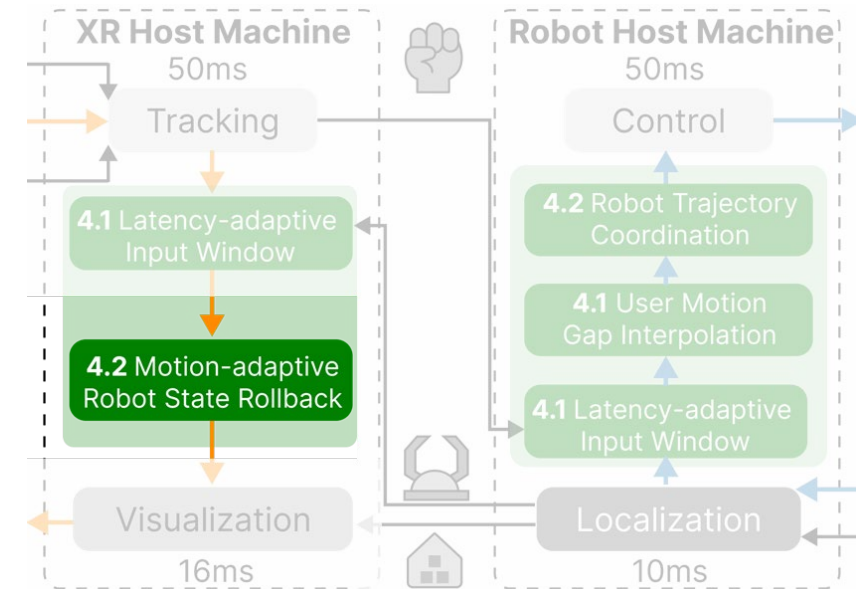
Motion-adaptive Robot State Rollback (XR side)

- When motion is too fast/abrupt to reconstruct reliably, roll back to an earlier reconstructed state
→ Nudges the user to slow down

Decision tree policy

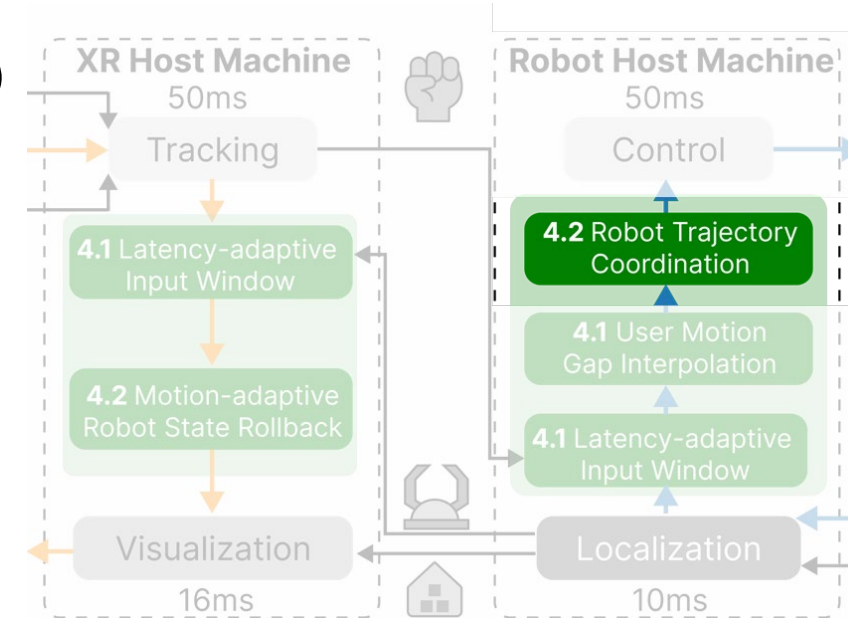
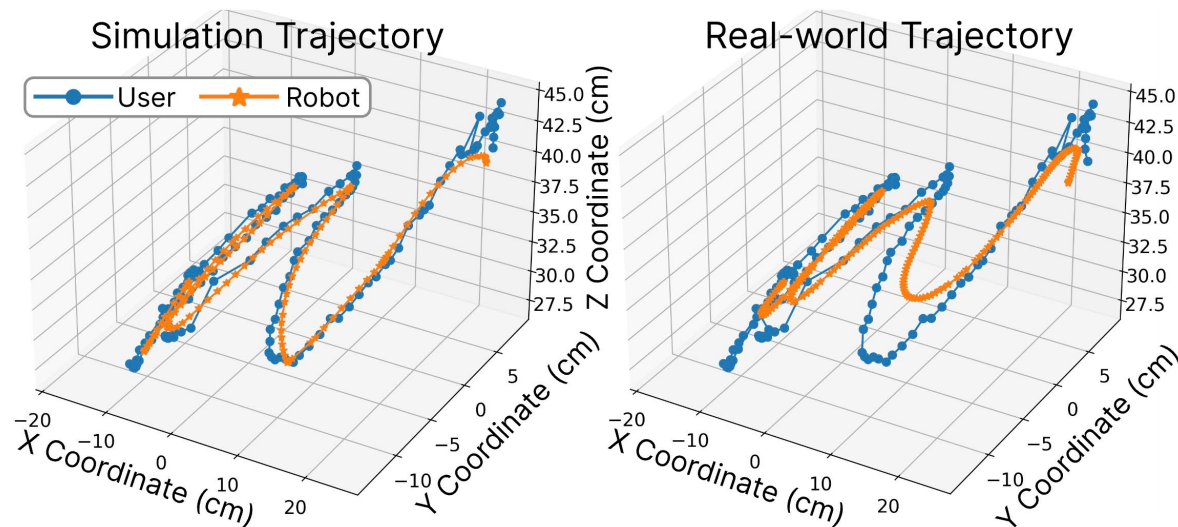
$$j_t = \pi_{\psi}(z_t), \quad j_t \in \{0, 1, \dots, J_{\max}\}$$

recent reconstructed state, user motion and network



Bidirectional Reconstruction: Motion Dynamics (C2)

Problem: Two views (robot local state vs. what user sees) are unaligned. Error is much higher in real robots.



Robot Trajectory Coordination (robot side)

- Fuses both views into one robot motion goal, weighted by reconstruction confidence α_t and link quality $\Pi_{\Omega}(\tilde{r}_{t+\Delta t})$.

$$g_t = (1 - \alpha_t) u^{\star} + \alpha_t \Pi_{\Omega}(\tilde{r}_{t+\Delta t})$$

Async Global and Sync Local Execution

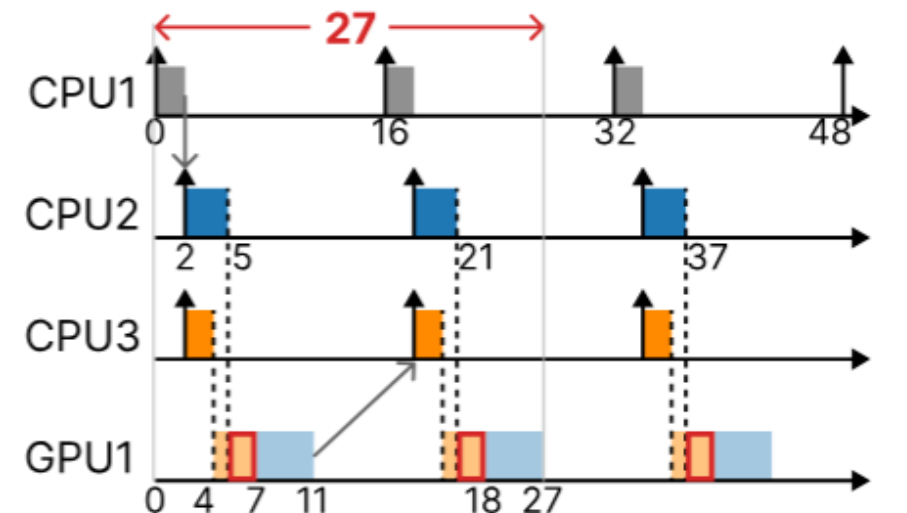
Asynchronous Global: Bidirectional reconstruction lets XR visualization and robot control run on independent timelines (sync only when network messages arrive)

How about Local component execution?

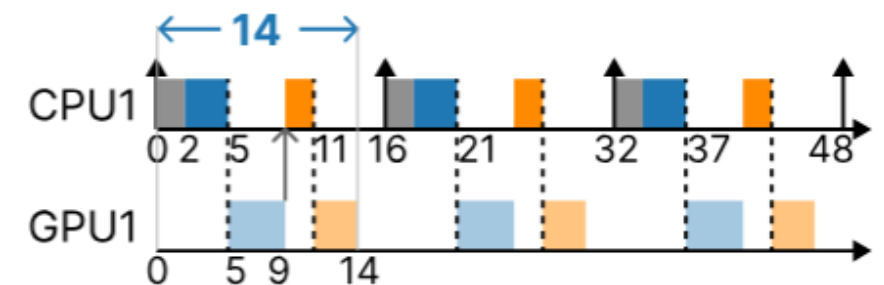
- Existing frameworks : asynchronous local execution with pub-sub mechanisms (DDS)
- Problem: each side has contention on shared resources → jitters & skipped executions

Our approach: Synchronous Local Execution

- Locally enforcing consistent ordering and cycle boundaries



(A) Rendering and Reprojection contention



(B) MATER Runtime Synchronization

Control/Data Plane Separation

Why separate?

- Existing frameworks send everything over DDS (ROS-compatible)
- Fine for small pose data, but not for large point clouds (needed for situation awareness)

Plane split in MATER

- Control plane (pose): DDS low overhead on small payloads
- Data plane (point cloud): UDP -- droppable without hurting control accuracy

Bandwidth-adaptive Point Cloud Scaling

- Scale down point-cloud data in object interior to reduce data transmitted while keeping structural integrity

Evaluation Setup

Hardware Platforms

- *Simulation*: PC hosted Gazebo* simulation with Kinova Gen3 manipulator
- *PC-to-PC*: Both XR and real robot are powered by PC with RTX 3060 GPU
- *Xavier-to-Nano*: XR powered by AGX Xavier and robot powered by Orin Nano

Motion

- Motion dataset: RoboSet** with 9,500 teleoperation traces
- Motion pattern with increasing complexity: *Linear, Curved, Oscillatory, Circular, and Segmented*

Network

- WLAN 5GHz and WLAN 2.4GHz, Cellular 5G and Cellular 4G
- XR and robot communicate through a cloud VPN server to control distance

* Nathan Koenig, and Andrew Howard. Design and use paradigms for gazebo, an open-source multi-robot simulator. 2004 IEEE/RSJ international conference on intelligent robots and systems (IROS)(IEEE Cat. No. 04CH37566)

** Vikash Kumar, Rutav Shah, Gaoyue Zhou, Vincent Moens, Vittorio Caggiano, Abhishek Gupta, and Aravind Rajeswaran.

RoboHyve: A unified framework for robot learning. Advances in Neural Information Processing Systems. 36. 2024

Evaluation Baselines

- **ROS Reality***: state-of-the-art XR teleoperation framework adopted in industry project
- **MATER-NoOp**: only the robot-side and XR-side reconstruction components
- **MATER: full MATER** system with all components and optimization

Ablation study is conducted by comparing MATER-NoOp and MATER

* David Whitney, Eric Rosen, Daniel Ullman, Elizabeth Phillips, and Stefanie Tellex. Ros reality: A virtual reality framework using consumer-grade hardware for ros-enabled robots. In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pages 1–9. IEEE, 2018.

MATER system overhead

- MATER incurs **6.7%** overhead on *PC-to-PC* configuration and only **3.6%** on *Xavier-to-Nano* configuration
- XR-side visualization on the *Xavier-to-Nano* is reduced by **13.4%** because of the local synchronization

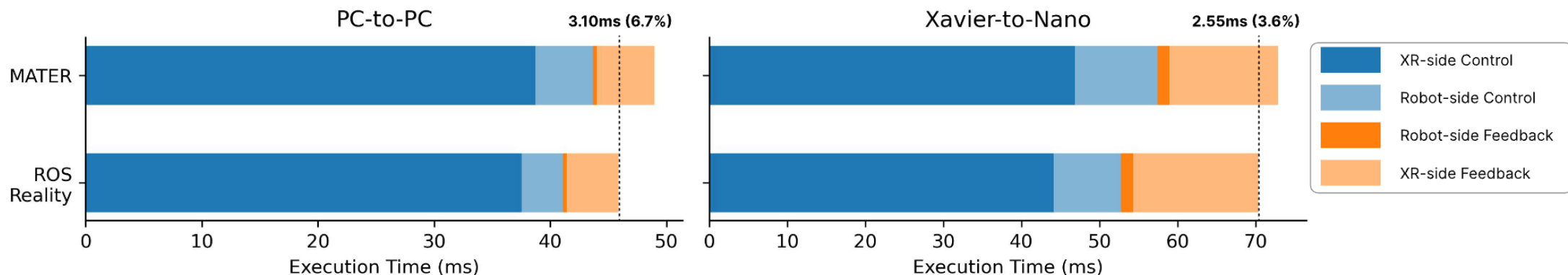


Fig. 9. MATER System Overhead.

Teleoperation Error

- MATER-NoOp: reduced **50.8%** under WLAN and **54.5%** under cellular networks
- MATER: reduced up to **69.8%** in WLAN and **73.1%** in cellular networks

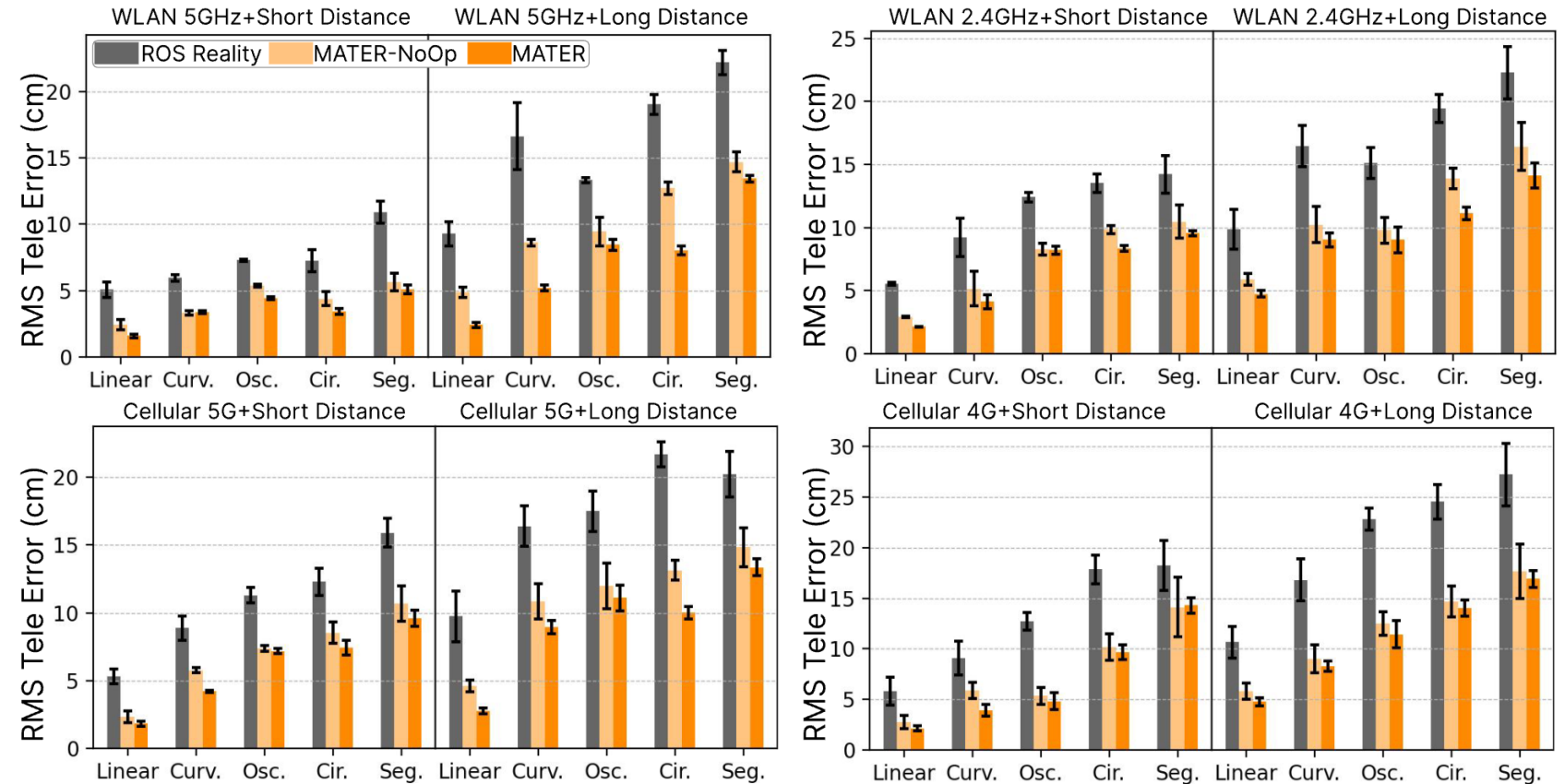
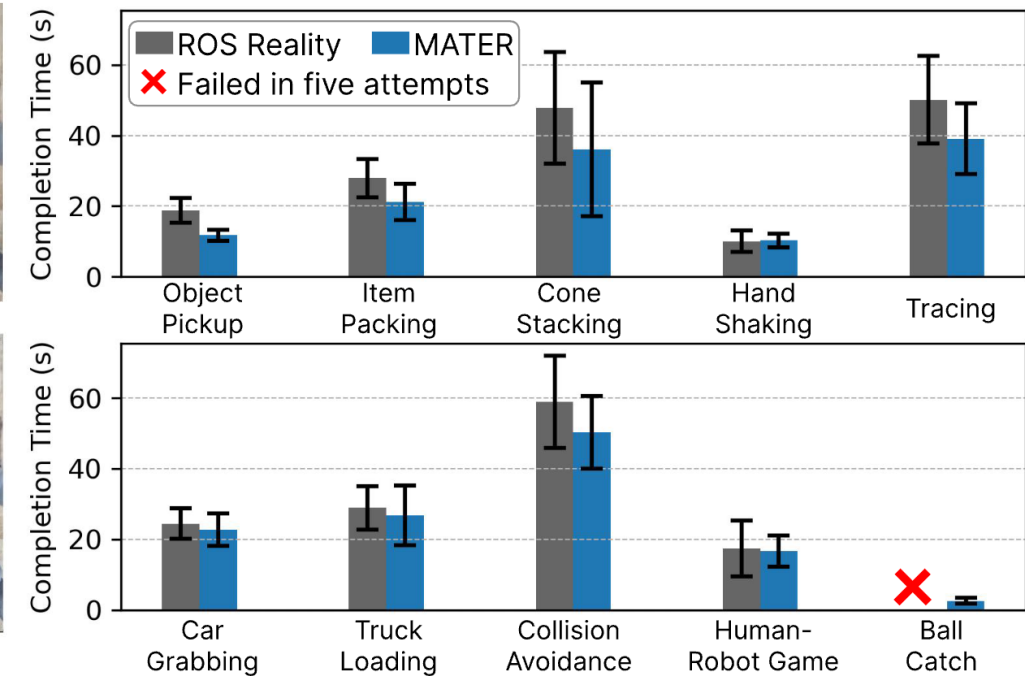
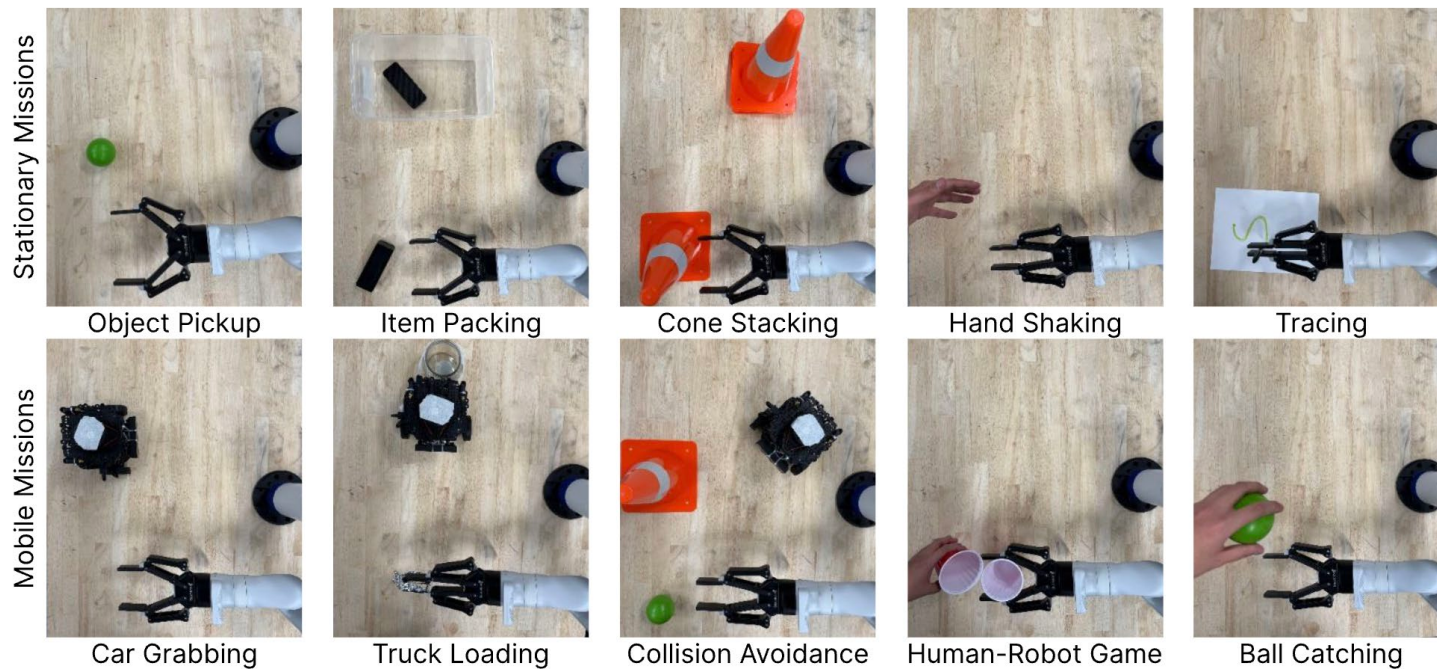


Fig. 11. Teleoperation Error comparison under PC-to-PC

Real-world Evaluation

- Real-world mission setup: both stationary and mobile missions
- Completion Time reduced by up to **37.7%** and teleoperation error by up to **57.2%**
- MATER can **accomplish ball catch**





Thanks for your attention!



MATER GitHub



Acknowledgment: This work was supported by the National Science Foundation (NSF) grants 1943265, 2312395, 2300525, 2312397, and 2343653.

