BOXR: Body and head motion Optimization framework for eXtended Reality

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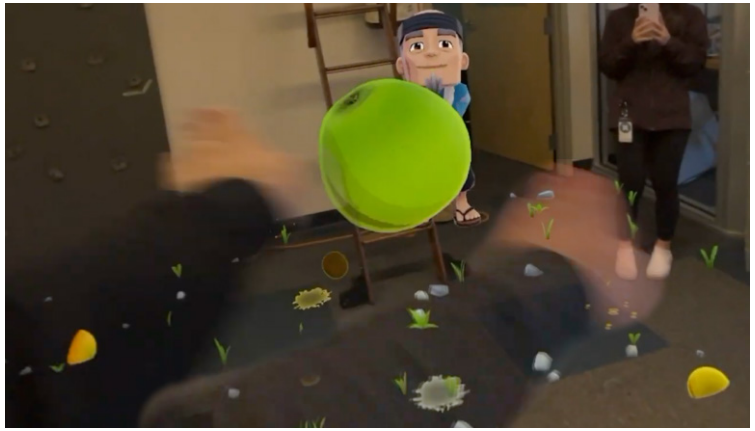
Extended Reality (XR)

What is Extended Reality (XR)?

- Creates an immersive virtual-physical user experience
- Includes Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR)

Why XR is useful?

- Intuitive control: user motion directly interact with virtual environment
- Diverse use cases: entertainment, teleoperation, accessibility, etc.



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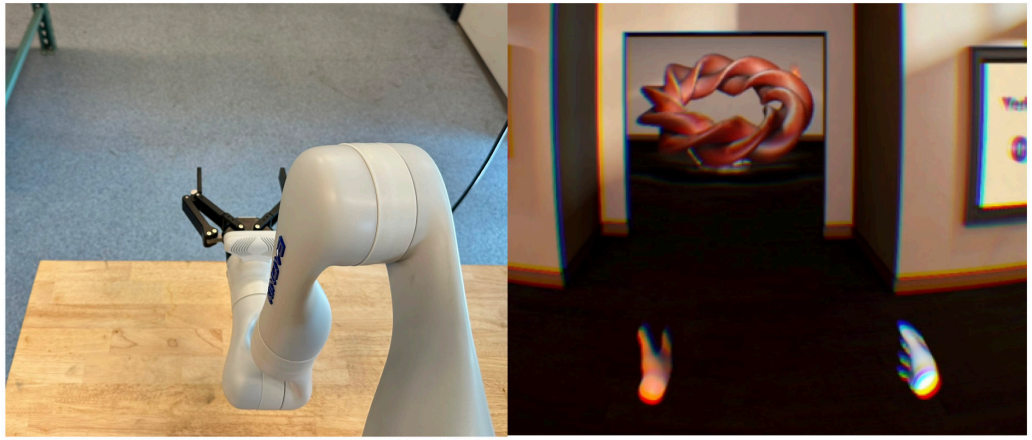
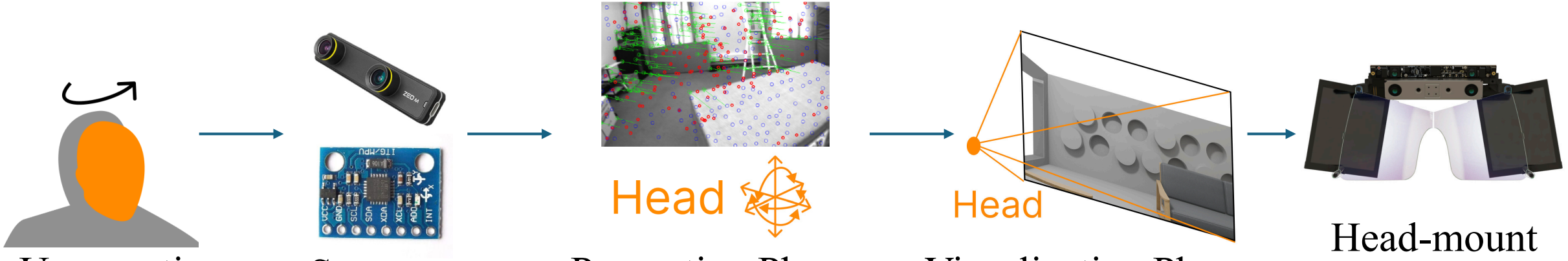


* iFixit, Vision Pro Teardown: Behind the Complex and Creepy Tech, https://youtu.be/JVJPAYwY8Us

XR pipeline and challenges

How XR systems work?



User motion → Sensors → Perception Phase → Visualization Phase → Head-mount Display (HMD)

Challenges of XR systems

- **Tight budget for motion display**: users can sense motion misalignment in 20ms*
- **Resource constraints**: standalone XR devices use embedded systems with limited computational resources

* Huzaifa, Muhammad, et al. "ILLIXR: Enabling end-to-end extended reality research." 2021 IEEE International Symposium on Workload Characterization (IISWC), 2021.

XR Sensors

Inertial Measurement Unit (**IMU**):

- Sample Rate: 500Hz ~ 1000Hz
- Data: acceleration and rotation

Stereo Camera (**CAM**):

- Sample Rate: 20Hz ~ 60Hz
- Data: a picture of surrounding information (With depth information)

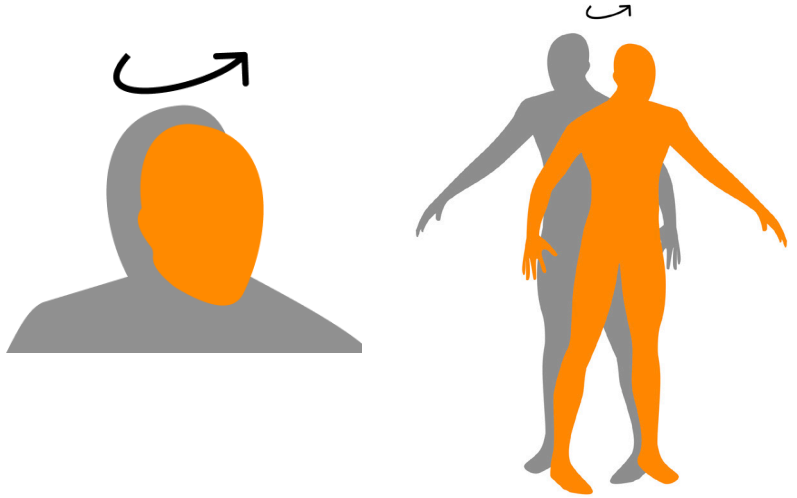
Apple Vision Pro sensors*

* Sarang Sheth, "Every Single Sensor inside the Apple Vision Pro and What It's Individually Designed To Do." https://www.yankodesign.com/2023/06/07/every-single-sensor-in-the-apple-vision-pro-and-what-its-individually-designed-to-do/

User Motion

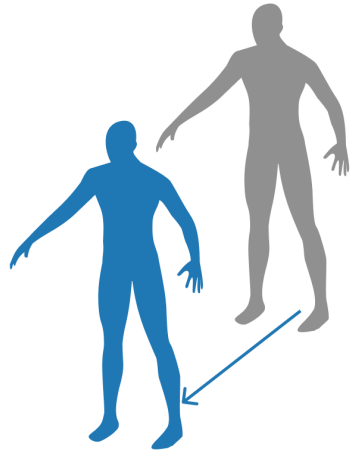
Head Motion

- Frequent rotational or small-magnitude translational movements
- i.e., head shaking, torso rotation, body leaning
- Can be accurately captured by **IMU**



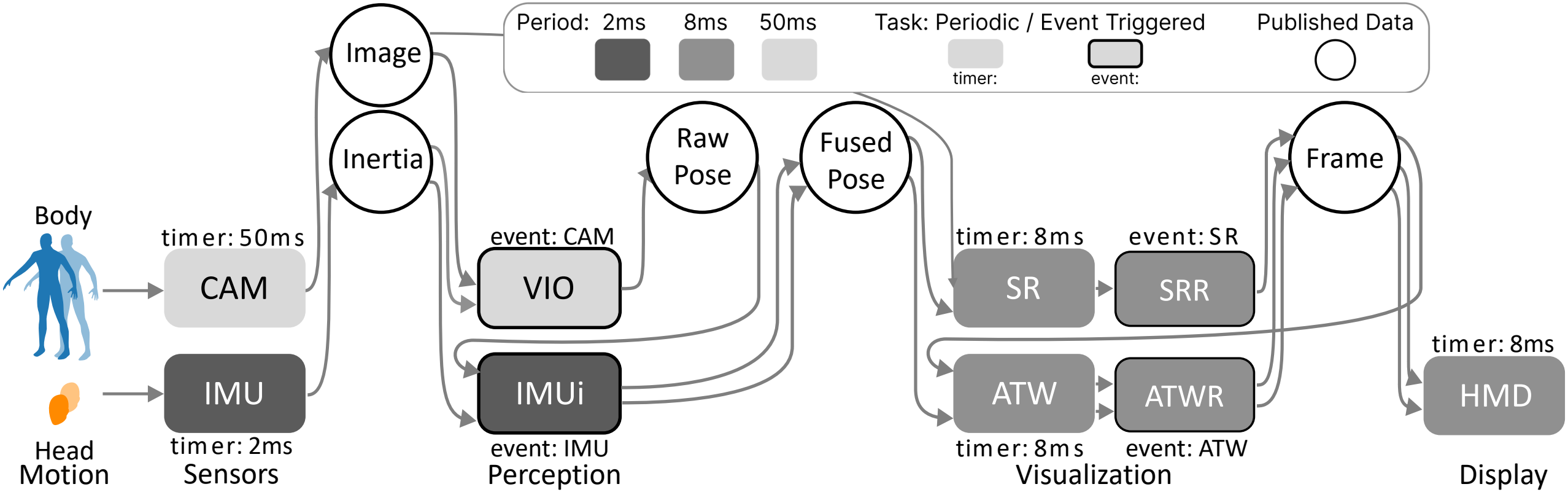
Body Motion

- Less frequent but with absolute position change in the environment
- i.e., running, walking, skiing, acceleration in car
- Requires **CAM** to perform accurate localization



State-of-the-art XR System Model: ILLIXR*

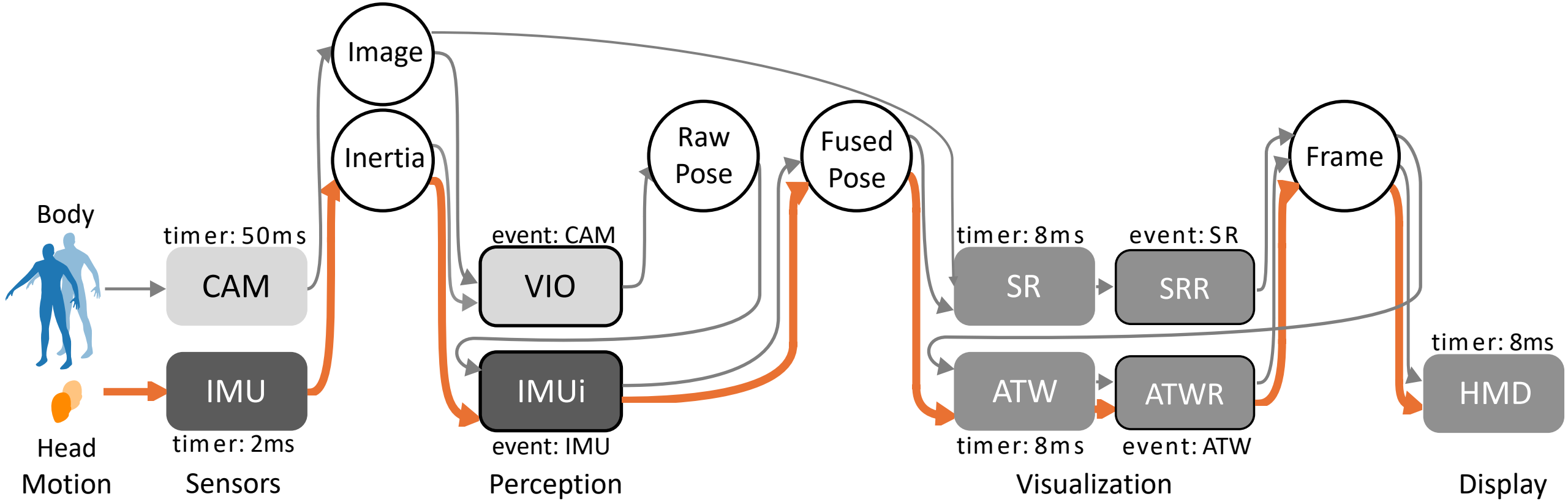
- Adopts a publisher-subscriber model
- Tasks: Visual Inertial Odometer (**VIO**), IMU integration (**IMUi**), Scene Reconstruction (**SR & SRR**), Asynchronous Timewarp (**ATW & ATWR**)



* Huzaifa, Muhammad, et al. "ILLIXR: Enabling end-to-end extended reality research." 2021 IEEE International Symposium on Workload Characterization (IISWC), 2021.

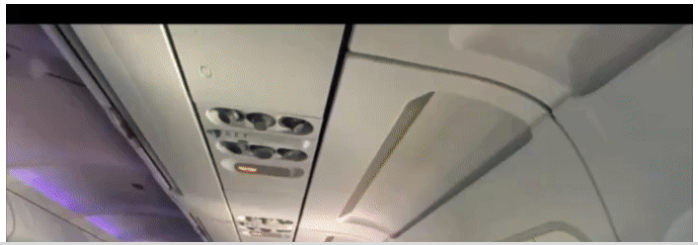
Existing metric: Motion-to-Display latency (M2D)

- Time between the **latest motion by the IMU** and its corresponding display on HMD
- **Why use M2D**? Most cases users just sit or stand idle without body motion

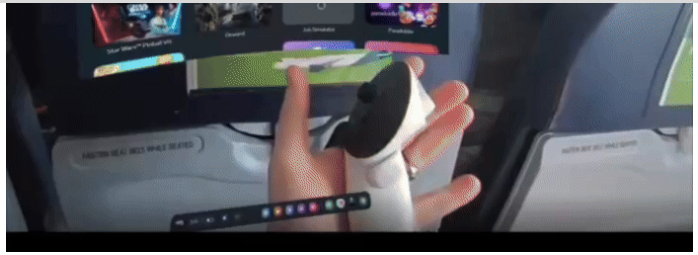


What if we only optimize M2D?

- Existing work achieves less than 20ms M2D, but when large body motion involved…



- Only **head motion** is accounted for in M2D
- **Body motion** is **NOT** considered in M2D metric and thus not optimized



Meta Quest 3 Taking Flight*

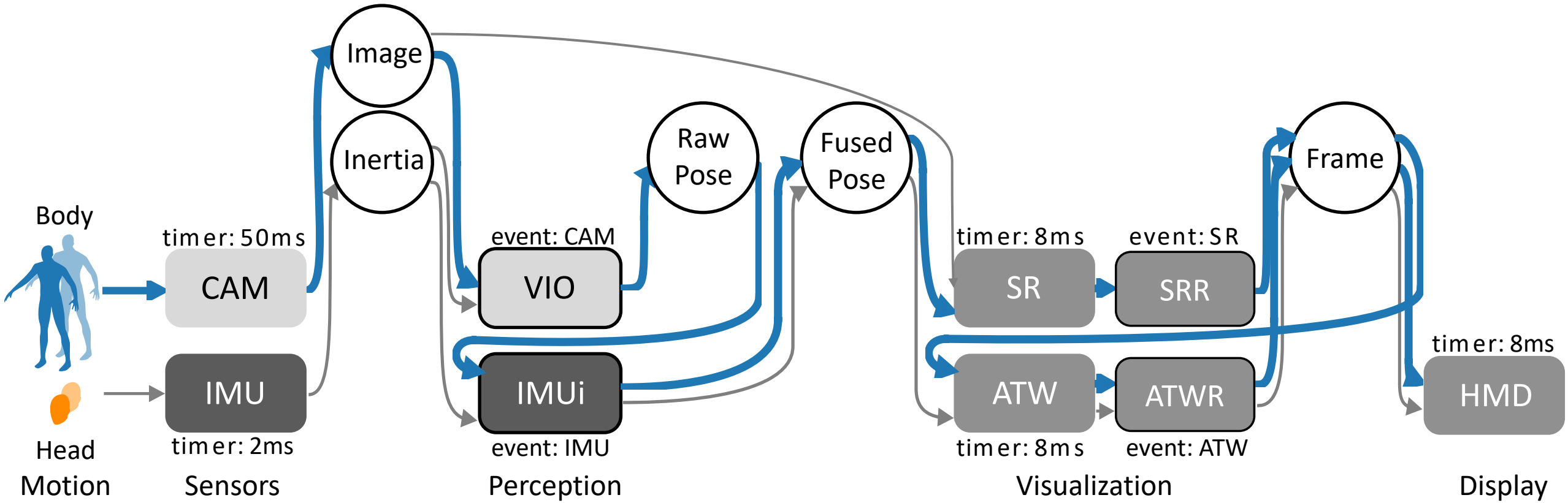
Apple Vision Pro Mountain Skiing**

- UI is supposed to move along with the user, but it drifts towards to edge of view!

* HistoricBeans, "Quest 3 in flight (passenger video)." https://www.reddit.com/r/OculusQuest/comments/17a8ctd/quest_3_in_flight_passenger_video/
** E. Cosner, "Snowboarding with apple vision pro - can this actually work? " https://youtu.be/LTVuGsYY2yc.

Introducing: Camera-to-Display latency (C2D)

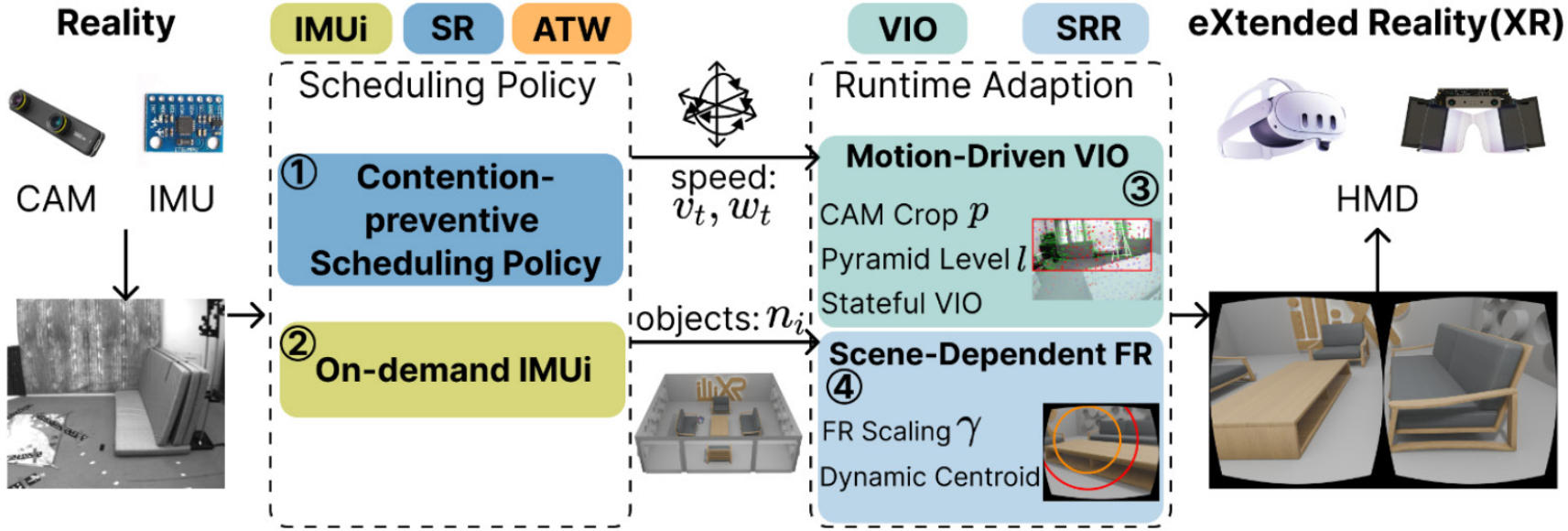
Time between the **latest body motion by CAM** and its corresponding display on HMD



Our Solution: BOXR

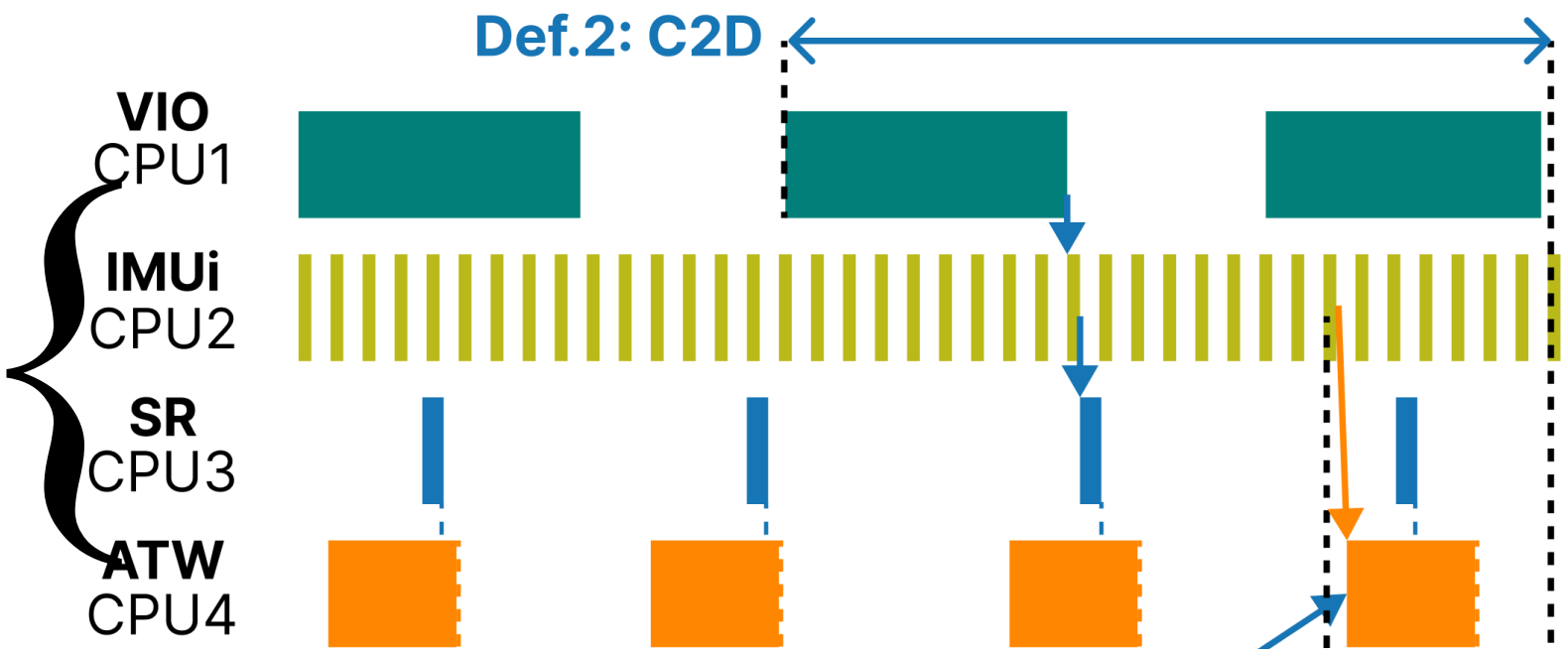
BOXR: Body and Head Motion **O**ptimization Framework for e**X**tended **R**eality

- Introduces the C2D metric to capture the delay from body motions
- Co-optimizes the delay from both body and head motions (M2D & C2D).
- Addresses unique challenges in XR systems:
  - Resource contention, optimization tradeoffs, and varying execution time due to motion and scene dynamics



System bottleneck

- XR adopts **publisher-subscriber** model
- **CPU** tasks: VIO, IMUi, SR, ATW

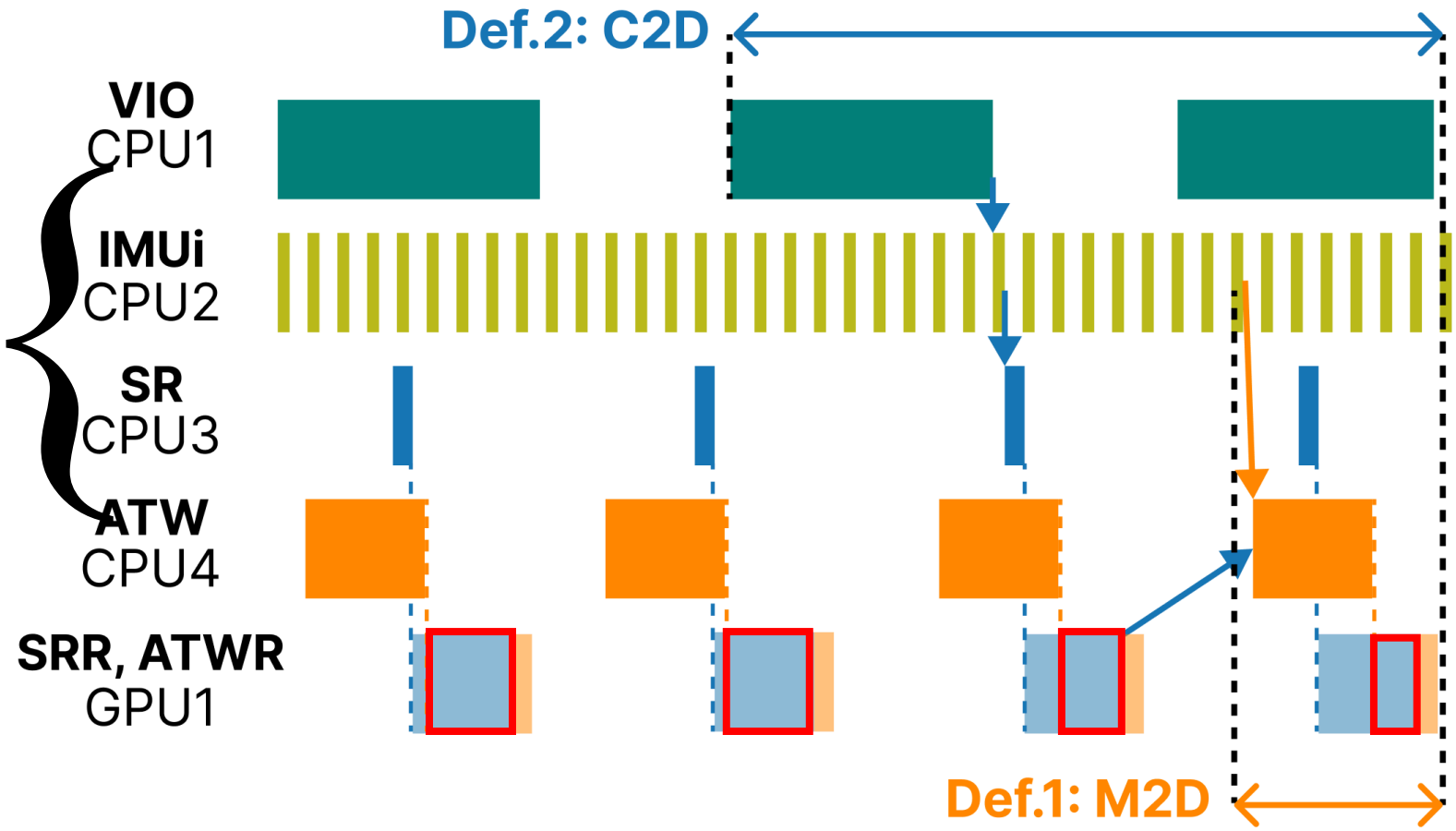


VIO	Visual Inertial Odometer
IMUi	IMU Integration

SR	Scene Reconstruction
ATW	Asynchronous Timewarp

System bottleneck

- XR adopts **publisher-subscriber** model
- **CPU** tasks: VIO, IMUi, SR, ATW
- **GPU** tasks: SRR, ATWR



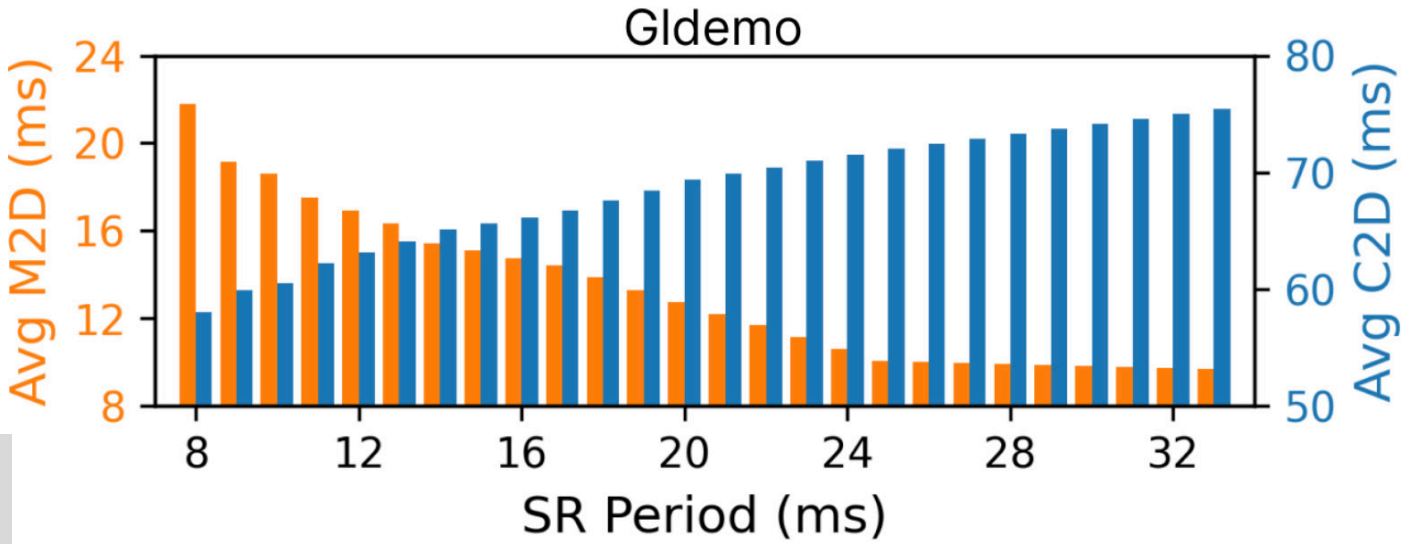
- **Contention** Between **SRR** and **ATWR**: Both tasks share the same stream and execute sequentially in a first-in-first-out order

M2D and C2D Tradeoff

- Single Optimization of M2D: increase SR period to mitigate contention

- However, C2D increases because less SR is executed: freshness of CAM data decreases

SR	Scene Reconstruction
ATW	Asynchronous Timewarp

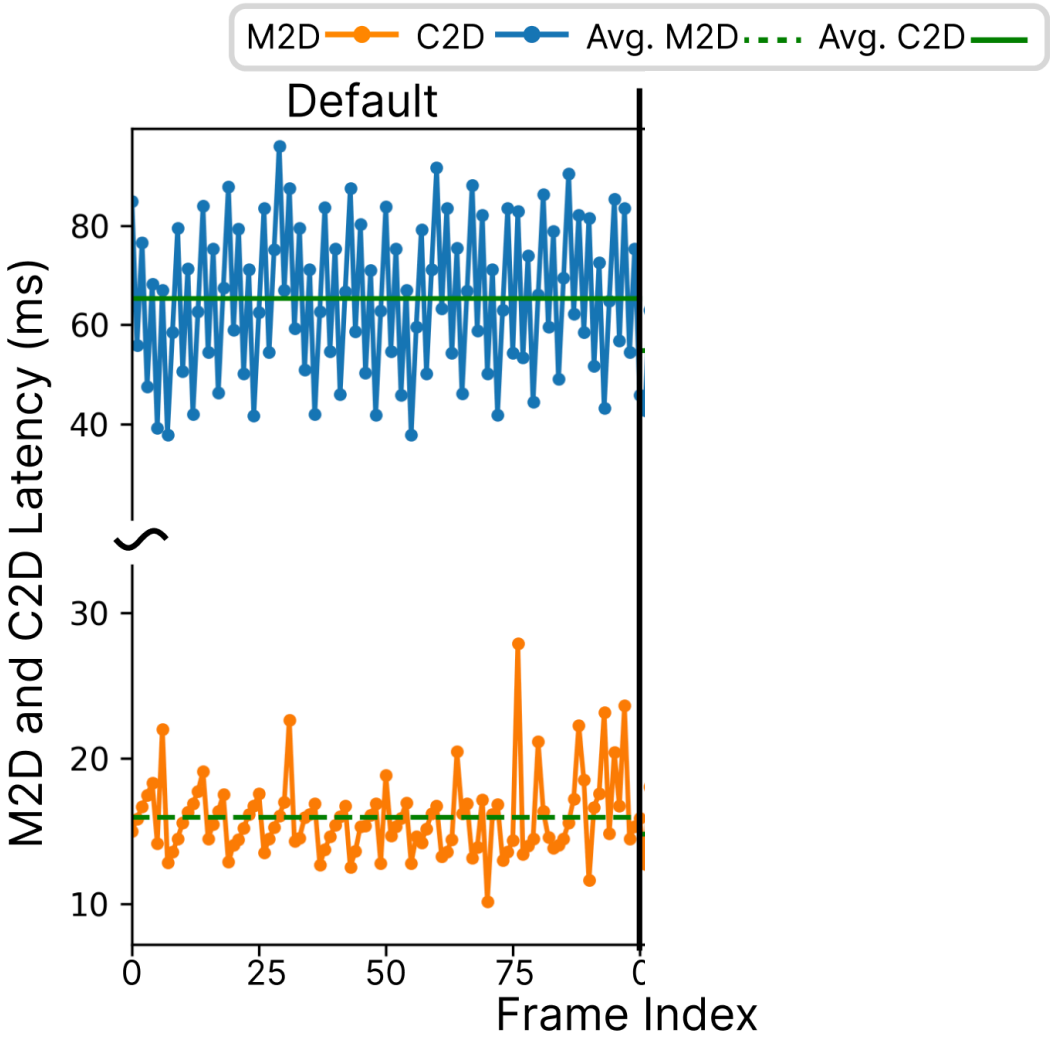


We need to consider both M2D and C2D during optimization

Simple Optimization of M2D and C2D does not work

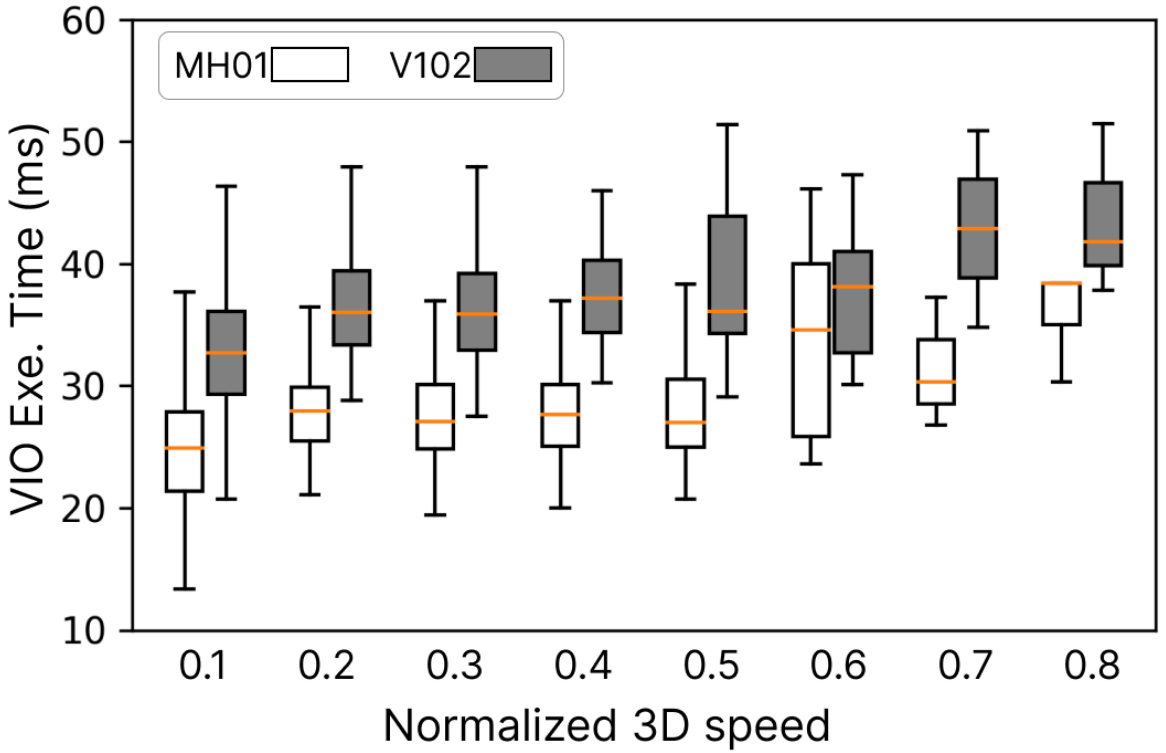
- Adjusting both SR and ATW period to minimize both average M2D and C2D
- But M2D and C2D fluctuations **increase**!
- Some Jobs have longer blocking time due to **contention**

Need to have scheduling policy that **prevents contention**!

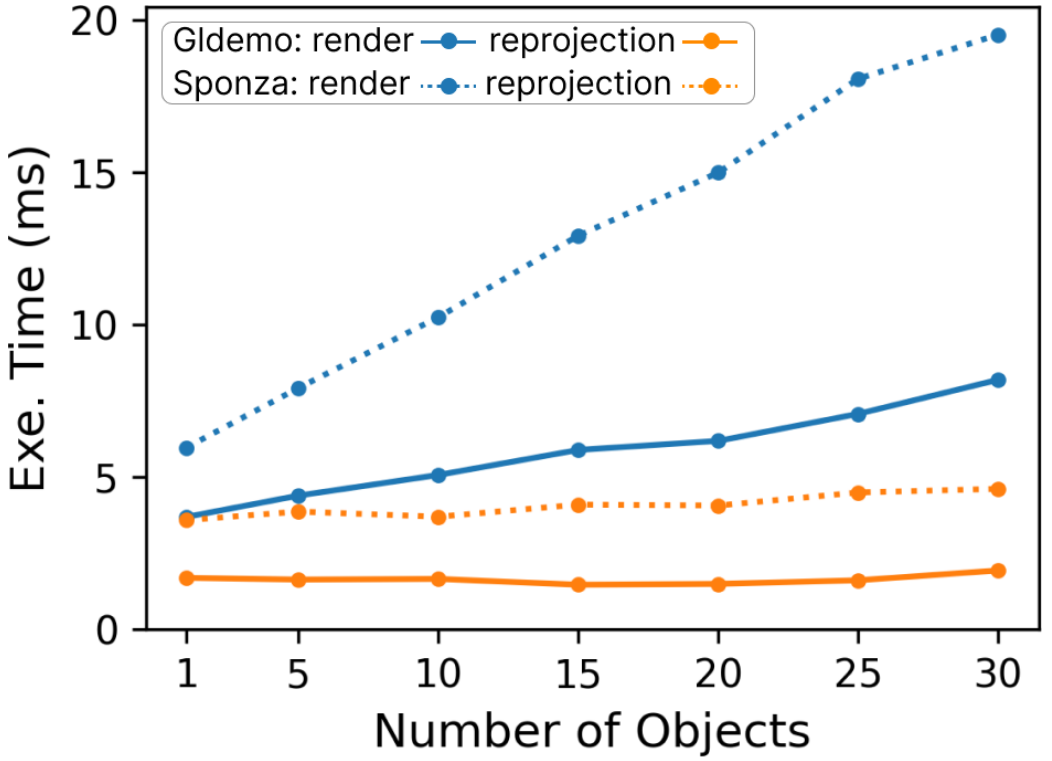


XR runtime characteristics

- **C1:** Motion-dependent Tracking: Larger speed increases VIO exec. time
- **C2:** Scene-dependent Rendering: More objects increase SRR exec. time (render)



C1: VIO Execution time increases with motion



C2: SRR Exe. time increases with Obj.

BOXR Overview

Why design a scheduler and runtime adaption

- Scheduling policy can be generated during setup to avoid large runtime overhead
- Motion and scene objects can only be acquired during runtime

BOXR Scheduling policy

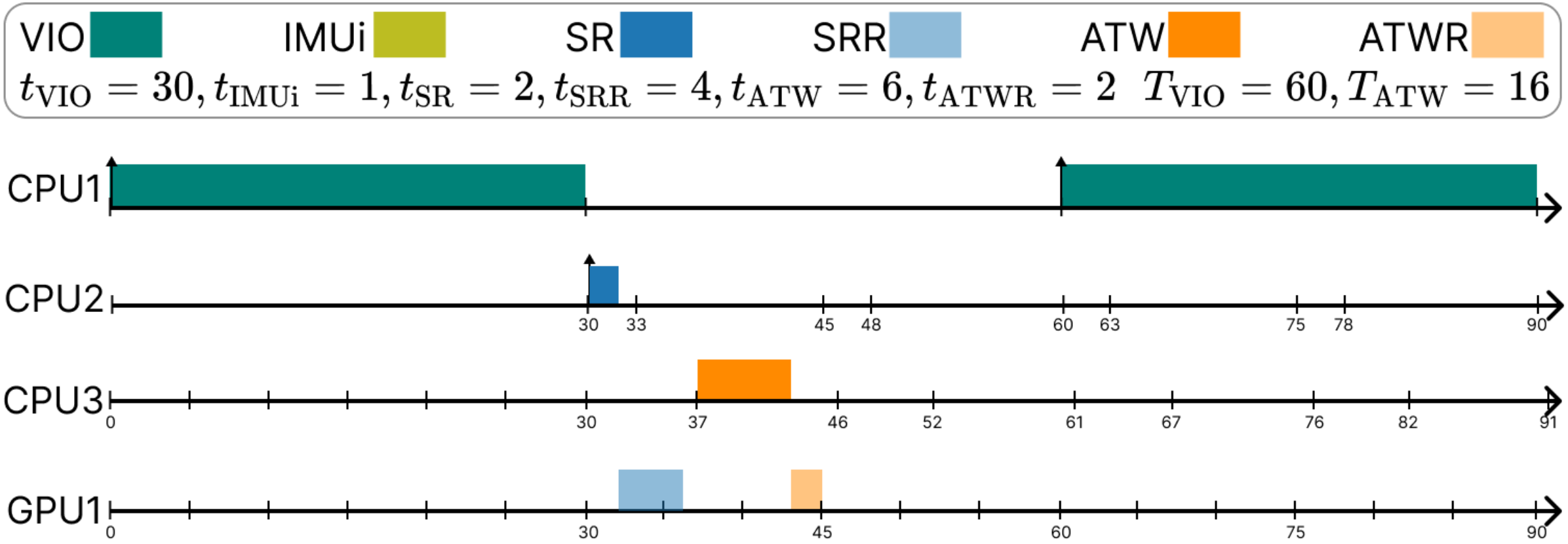
- Contention-preventive scheduling: Prevents contention between SRR and ATWR while maintain the fresh raw pose information
- On-demand IMUi: Executes IMUi only when fused pose is needed

BOXR Runtime Adaption

- Motion-Driven VIO: Addresses **C1:** motion-dependent tracking
- Scene-Dependent Foveated Rendering: Addresses **C2:** scene-dependent rendering

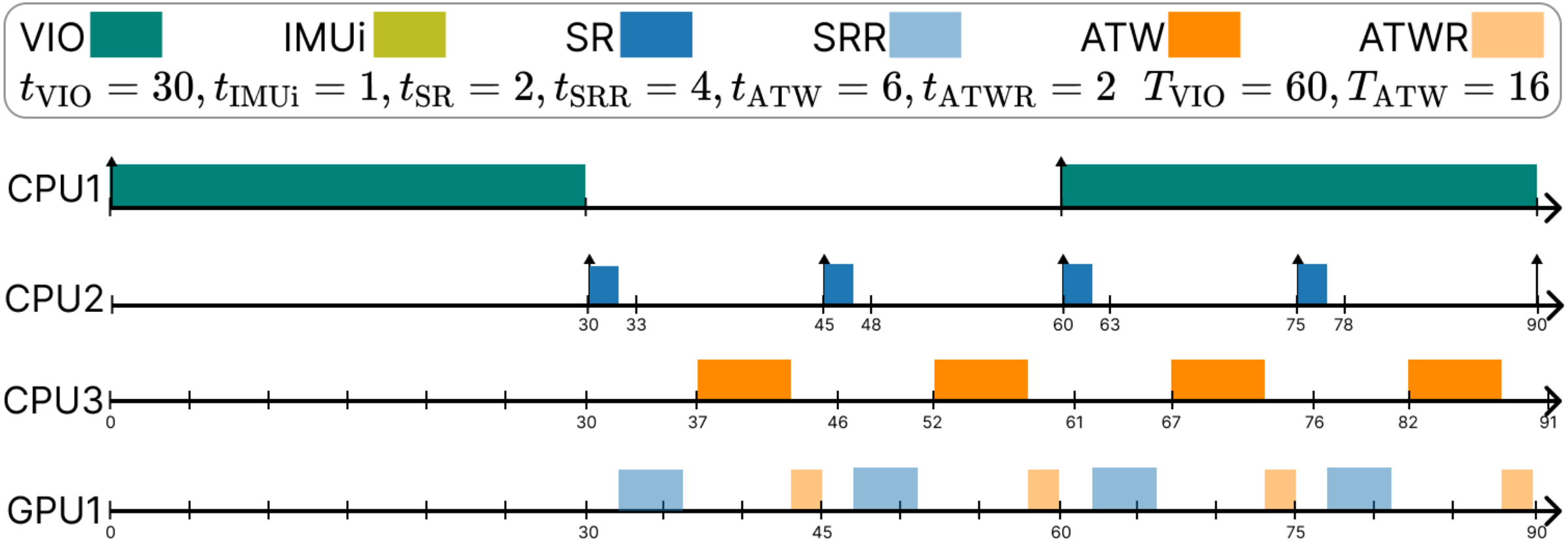
BOXR Scheduling policy: Contention-preventive

- To avoid contention between ATWR and SRR, BOXR schedules ATW and ATWR jobs synchronously to SR and SRR jobs



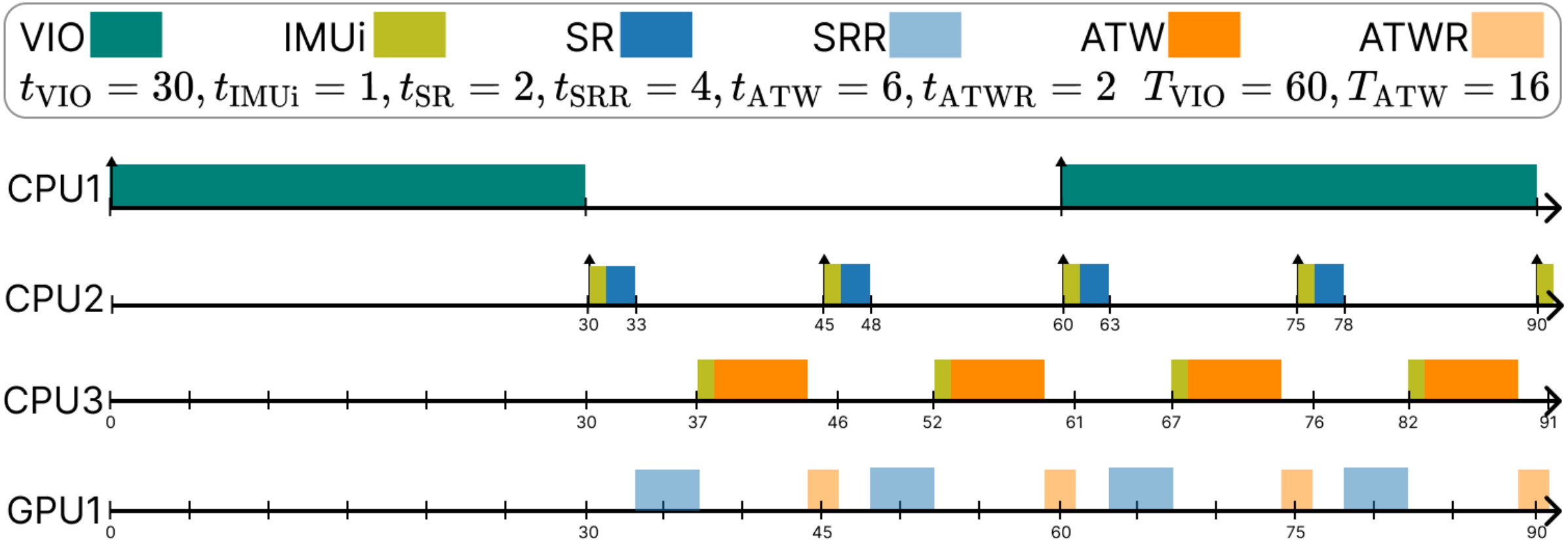
BOXR Scheduling policy: Contention-preventive

- To maintain raw pose data freshness, BOXR determines the SR period that ensures each C2D sequence (VIO→IMUi→SR→SRR→ATW→ATWR) completes with no temporal overlap



BOXR Scheduling policy: On-demand IMUi

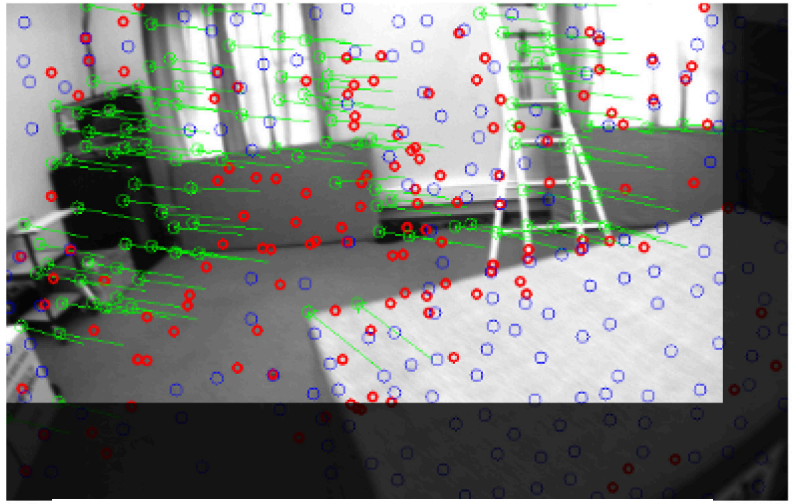
- To avoid wasted IMUi jobs, BOXR schedules IMUi to run only at the beginning of SR or ATW jobs

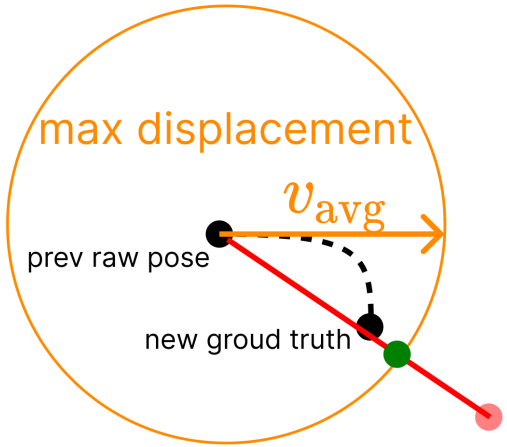


Runtime Adaption: Motion-Driven VIO

Goal: Manage the varying execution time of VIO while minimizing pose quality degradation

- **Image cropping**: when motion is large, crop the image input
- **Level of pyramid adjustment**: adjust the pyramid level in the VIO's Multi-state Kalman Filter w.r.t motion
- **Error bounding**: leverage the previous raw pose to calculate the maximum possible displacement. Bound the output pose within the displacement.

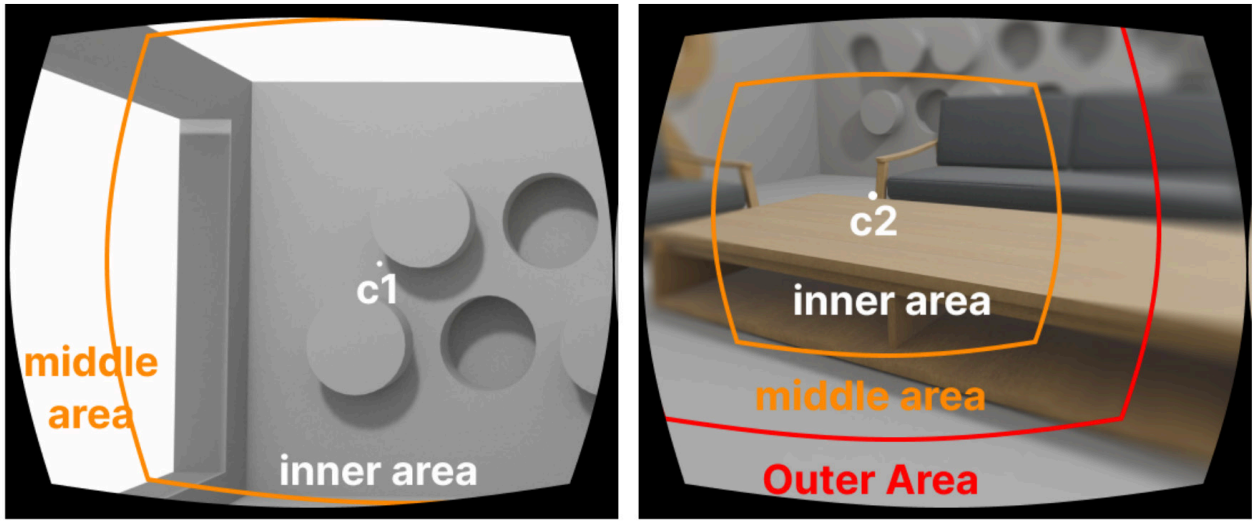




Runtime Adaption: Scene-Dependent Foveated Render

Goal: Control varying SRR execution time by scene-adaptive foveation

- **Dynamic foveation area**: reduce the peripheral resolution when more objects are in the viewport
- **Dynamic Objects Centroid**: fix the center of foveation to the objects' centroid to effectively reduce render time



Evaluation and Baselines Setup

Setup:

- Hardware Platform: PC, NVIDIA AGX Xavier, NVIDIA Orin Nano
- XR applications: Table I
- Trajectory: Table II

TABLE I: Evaluated XR Applications

	Sponza(Spon)	**Materials**(Mat)	**Gldemo**(Gl)	**Platformer**(Plat)
Object	32	81	7	3014
Vertex	192870	62826	54760	26168
Texture	33	24	8	4

TABLE II: EuRoc MAV Dataset Categorization

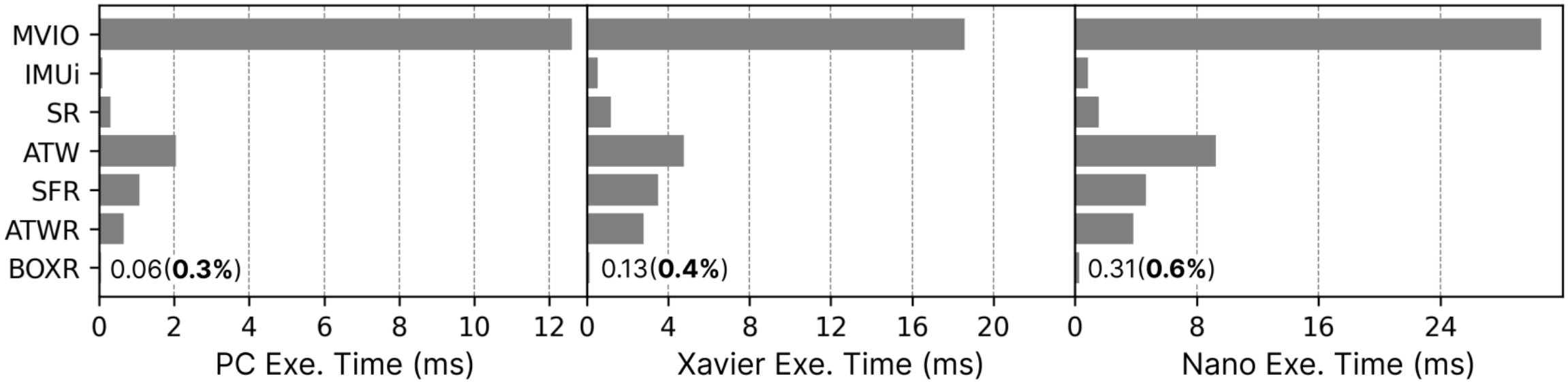
	No Motion	**Small Motion**	**Med. Motion**	**Large Motion**
$v_{3D}(m/s)$	$[0, 0.1)$	$[0.1, 1)$	$[1, 2)$	$[2, \infty)$
Perc(%)	10.62	66.75	20.30	2.33

Baselines:

- ILLIXR: Pub-Sub model
- ILLIXR-OP: Optimized with SR and ATW periodicities changes
- BOXR-S: Static BOXR only implements the BOXR scheduler
- BOXR: Complete framework with both scheduler and runtime adaption

Efficiency: Low Runtime Overhead

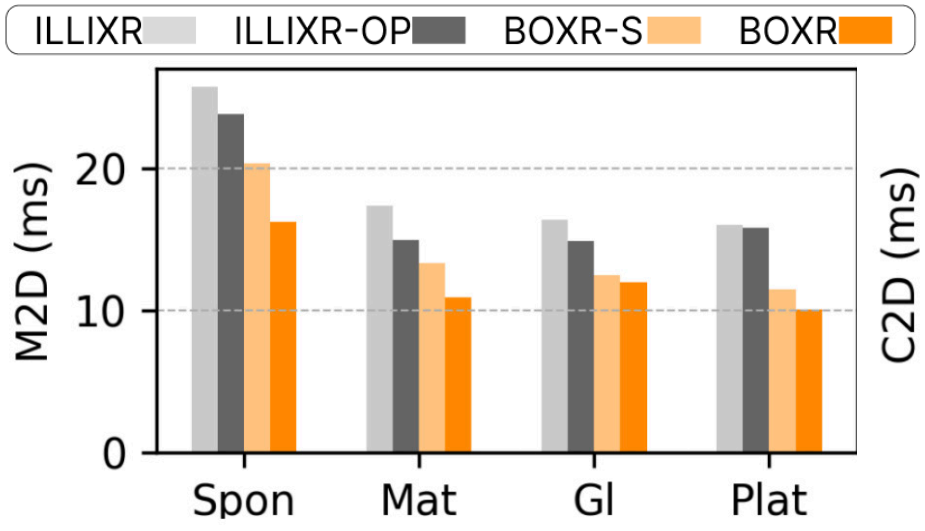
- BOXR runtime adaption only results **up to 0.6%** of system overhead

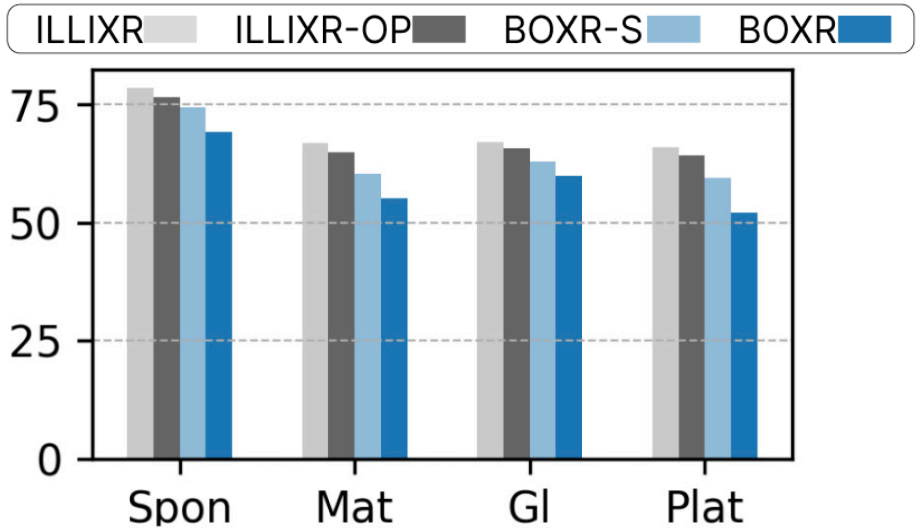


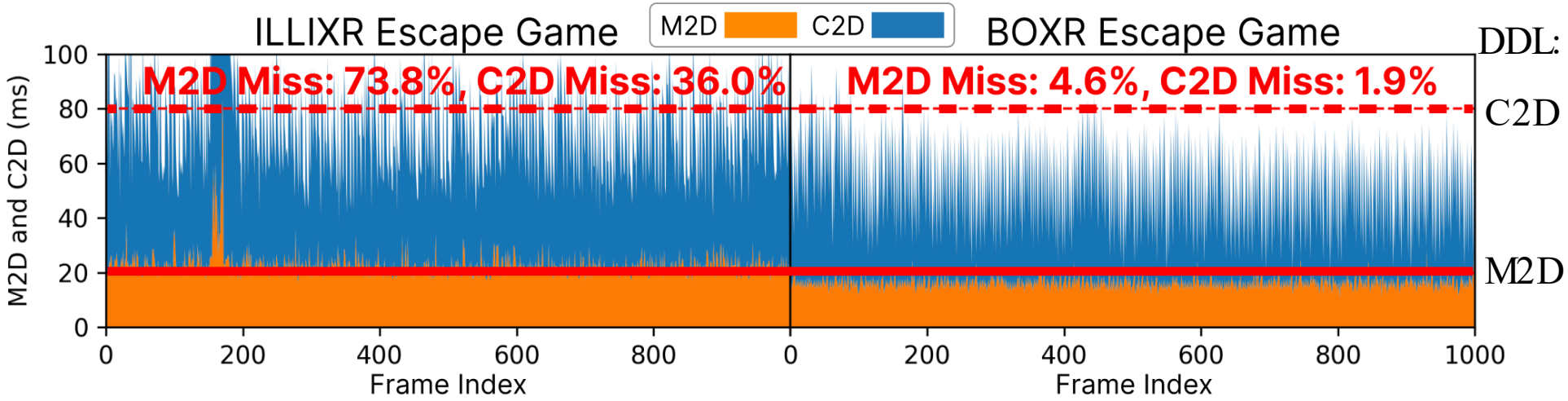
Effectiveness: M2D and C2D Reduction

BOXR General **Effectiveness**:

- Xavier: on average **37%** M2D and **27%** C2D reduction
- Real-world Gaming: BOXR reduces M2D and C2D miss rate by **69.2%** and **34.1%** respectively







Conclusion

- Discovers the C2D metric and co-optimize both M2D and C2D for both body and head motion
- Addresses resource contention and increased execution time due to motion and objects

GitHub Link

Paper Link