IEEE/ION PLANS 2025, Session D6b: Smartphone-Based Localization, 1st May 2025

A Method to Estimate User Position and Orientation Based on Relative Position Measurement Between a Navigation Robot and a Smartphone

Satoki Ogiso[1], Daisuke Sato[2], Ryosuke Ichikari[1], Takahiro Miura[1],
Masakatsu Kourogi[1], Takashi Okuma[1], Takeshi Kurata[1], and Takeshi Tanabe[1]

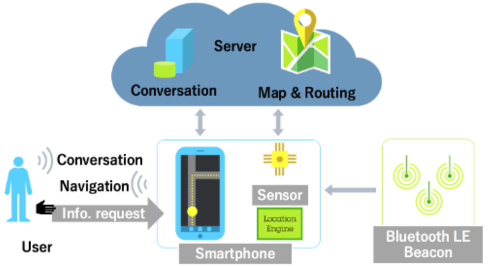
1: National Institute of Advanced Industrial Science and Technology (AIST)

2: Carnegie Mellon University

Background

Understanding of spatial relationship — Ability to move from place to place

- Support for **Orientation & Mobility (O&M)** of people with visual impairment
- Navigation assistants with smartphones
  - Do not limit user's **mobility** while inaccurate **orientation**
  - Requires investment in the environment (tags, feature point maps, etc.) & maintenance
  - Difficult to point at markers for people with VI
- Navigation robot
  - Reduces user’s cognitive load by precise **orientation**
  - Sometimes restricts user’s **mobility**
- Combination of these methods enables complementary navigation



[D. Sato+, 2017]

https://www.linkx.dev/shikai

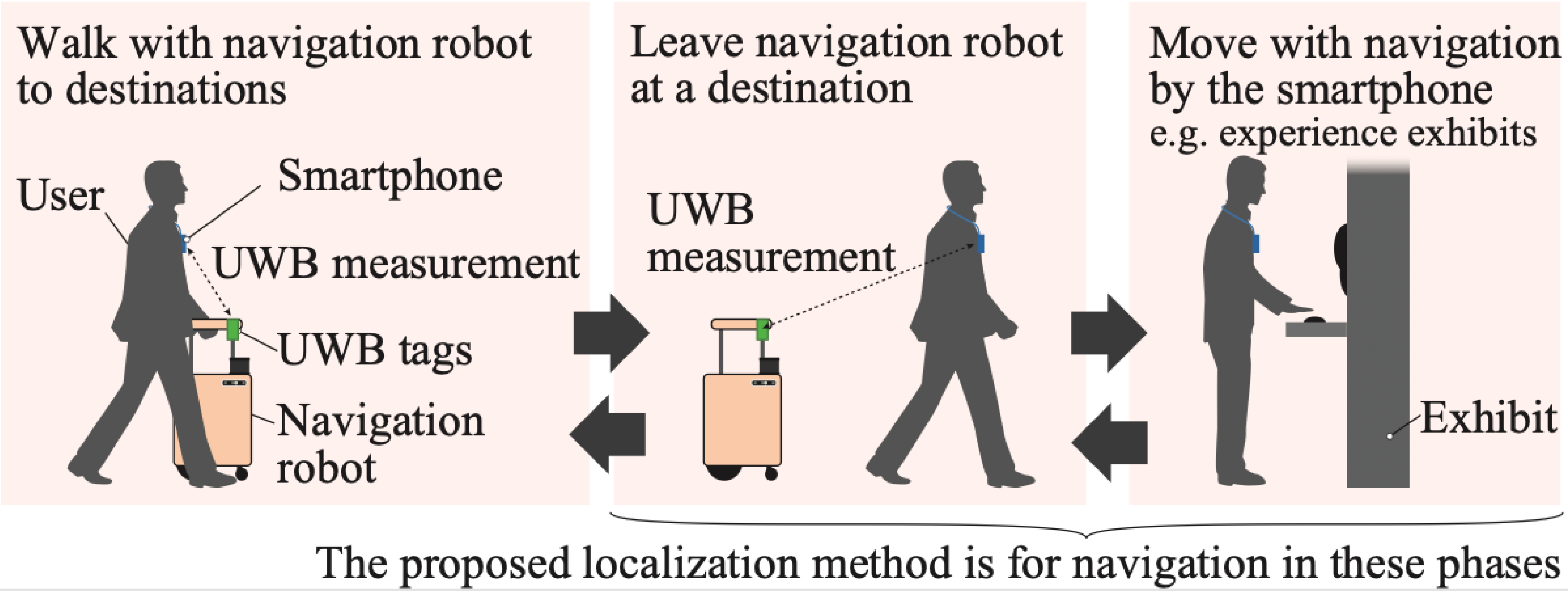
[T. Takagi+, 2022]

Permanent operation in EXPO 2025 & Miraikan - The National Museum of Emerging Science and Innovation

VI: Visual impairment

Purpose & Approach

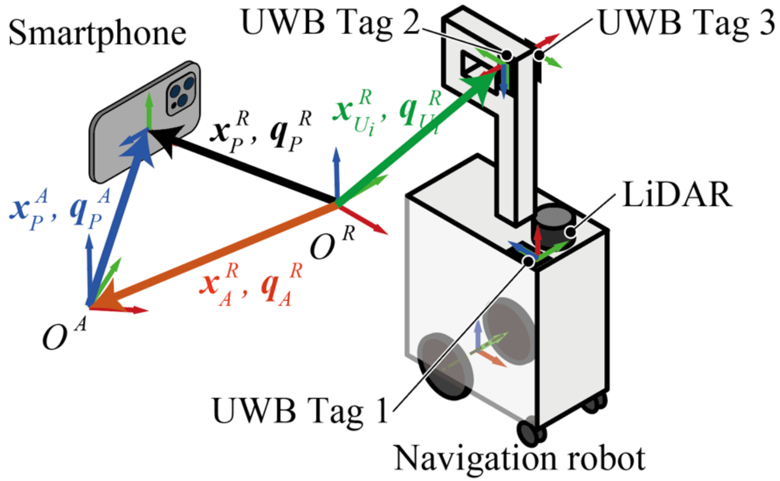
- **Assumption**: navigation robot is available in the target venue
- **Purpose of this paper**: smartphone's localization in sub-meter accuracy without additional infrastructural investment & maintenance
- **Approach**: estimate the smartphone's location by utilizing a navigation robot as a reference point using relative position measurement by UWB

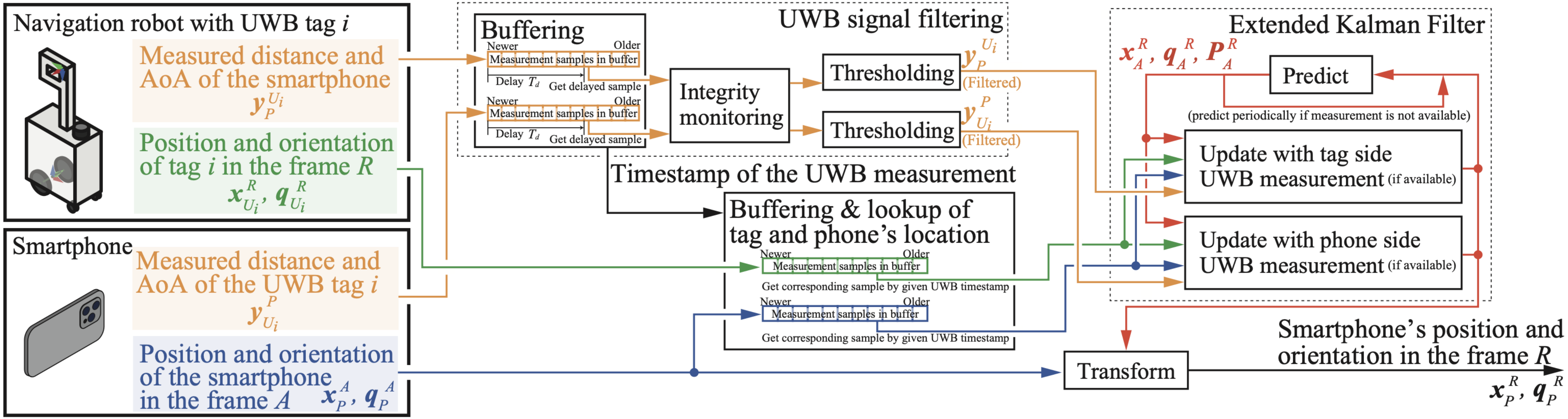


UWB: Ultra-wide band

Overview of the proposed method

- The proposed method estimates the smartphone's location and orientation in the frame R (global frame)
- Proposed method consists of UWB signal filter, extended Kalman filter and transformation

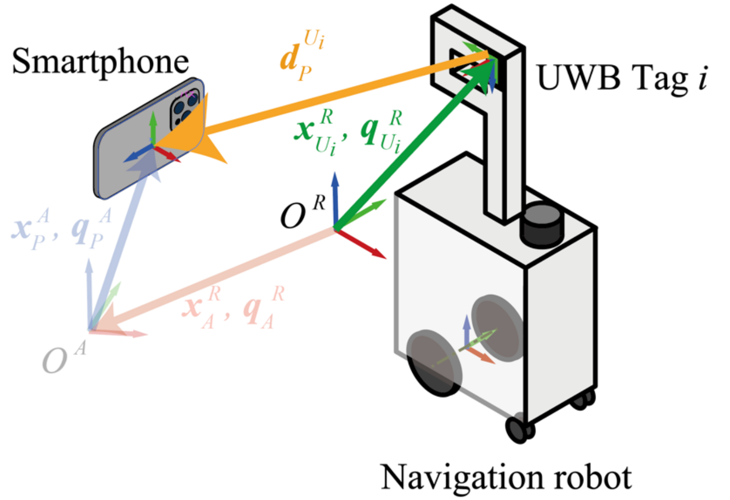


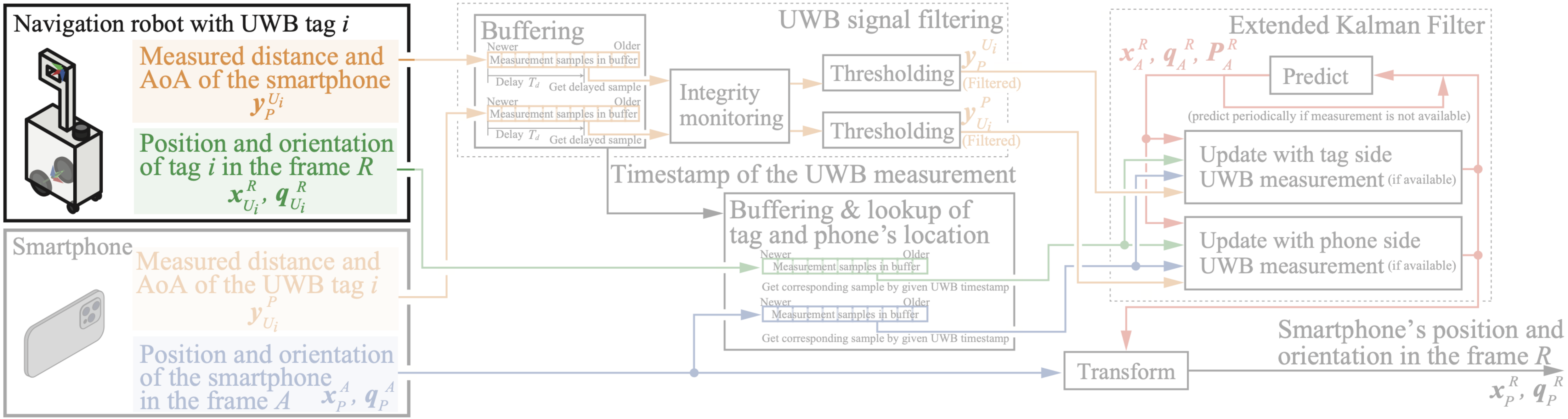


AoA : Angle of arrival
UWB: Ultra-wide band

Measurement at the navigation robot

- Measures UWB distance and AoA (=relative location) of the smartphone in the tag's local frame
- Tag's location/orientation : determined from navigation robot's localization/orientation



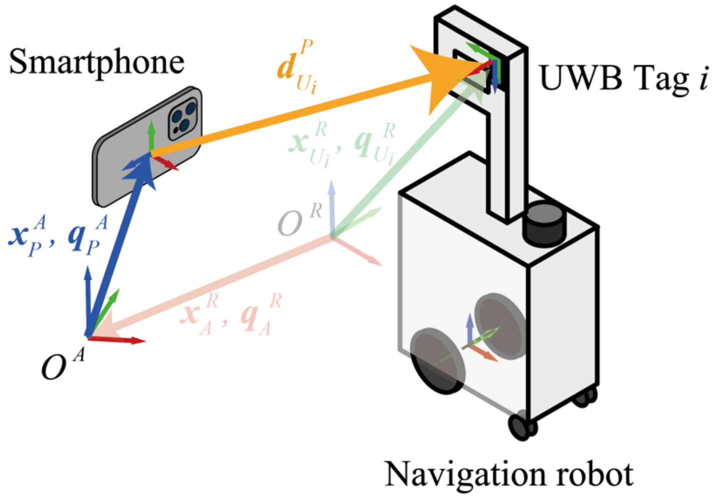


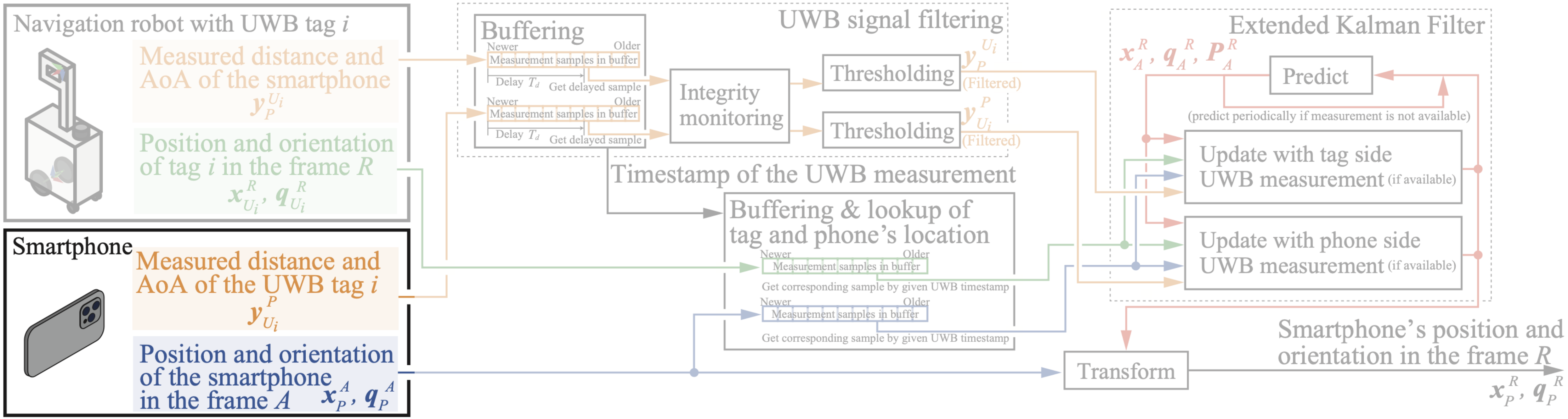
IMU : Inertial measurement unit
LiDAR: Light detection and ranging
AoA : Angle of arrival
UWB: Ultra-wide band

Measurement at the smartphone

Carnegie Mellon University   AIST Create the Future, Collaborate Together

- Measures UWB distance and AoA (=relative location) of the tag in the smartphone's frame
- Smartphone's location/orientation $\boxed{x_P^A, q_P^A}$ in its frame A : measured by visual-inertial odometry (ARKit)
- Z axis of both frames R, A are aligned with vertical direction

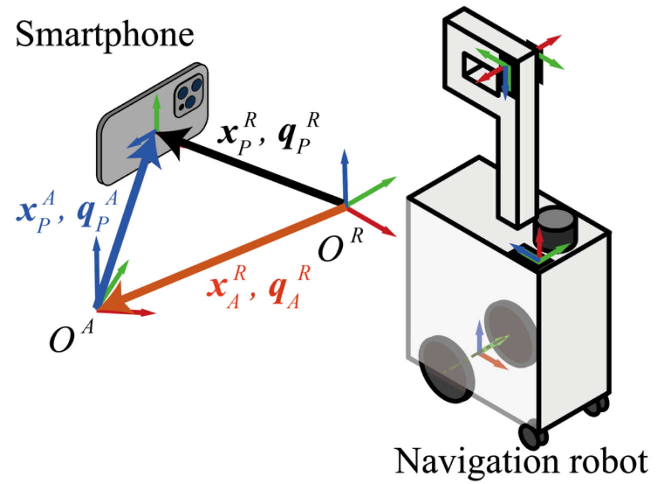


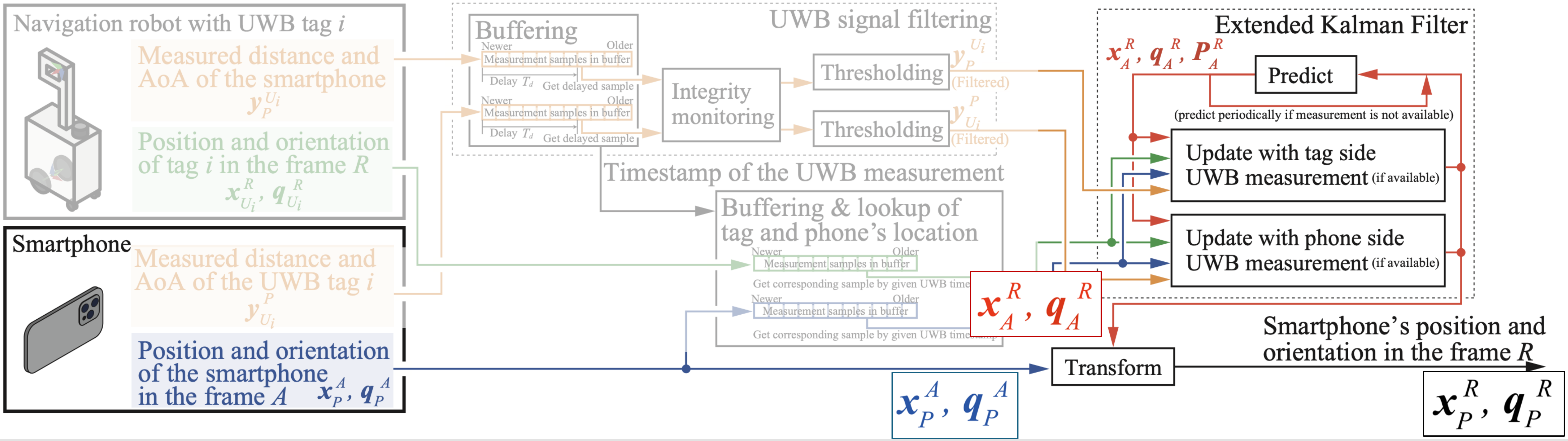


IMU : Inertial measurement unit
LiDAR: Light detection and ranging
AoA : Angle of arrival
UWB: Ultra-wide band

Target of estimation: origin of the VIO

- Estimate origin of VIO (frame A) $\boxed{\boldsymbol{x}_A^R, \boldsymbol{q}_A^R}$ in frame R by EKF
  - Should be tracked over time as VIO may drift.
- Update EKF if UWB measurement is available after filtering (next slides)
- The smartphone's position an orientation at frame R $\boxed{\boldsymbol{x}_P^R, \boldsymbol{q}_P^R}$ is obtained by transforming with $\boxed{\boldsymbol{x}_P^A, \boldsymbol{q}_P^A}$ the origin $\boxed{\boldsymbol{x}_A^R, \boldsymbol{q}_A^R}$



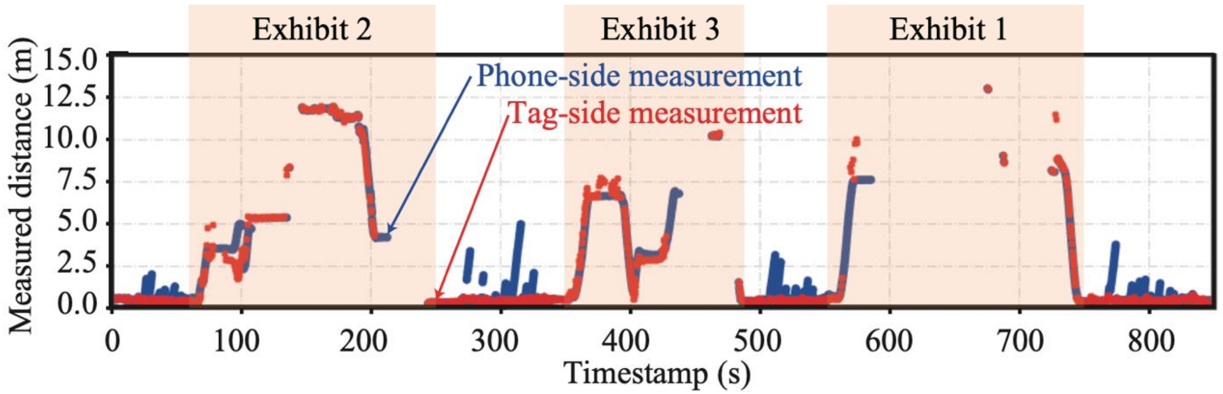


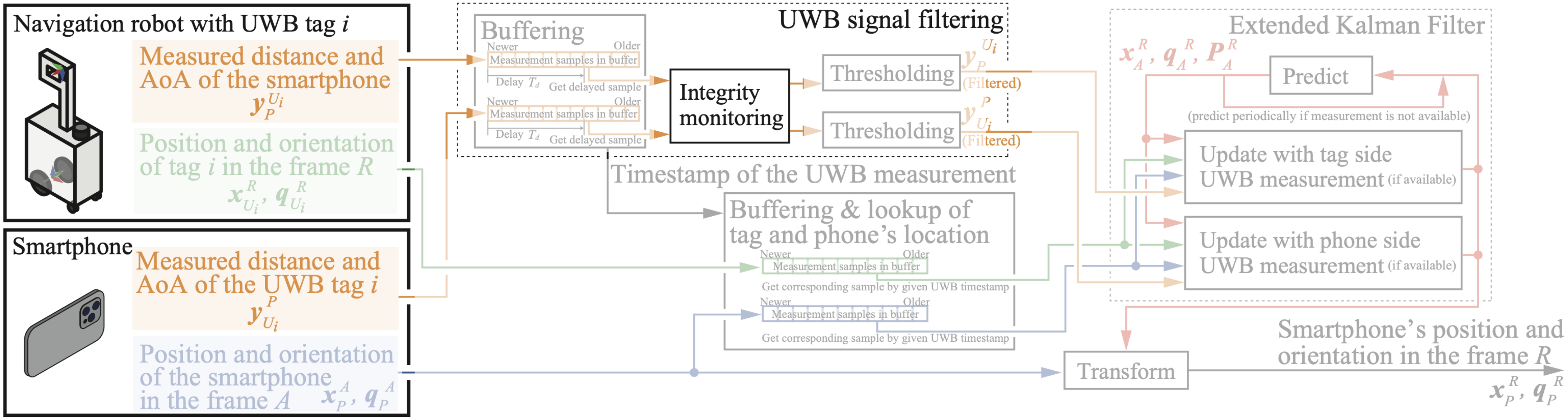
VIO: Visual-inertial odometry
EKF: Extended Kalman filter
AoA : Angle of arrival
UWB: Ultra-wide band

Detail of UWB signal filtering (1/3)

- **Integrity monitoring**
  - The ranging result should be the same at both sides (UWB two-way ranging)
  - Ignore unintended behavior of internal filtering of the smartphone
  - Check if tag-side and phone-side range within a threshold

Example of a measurement result



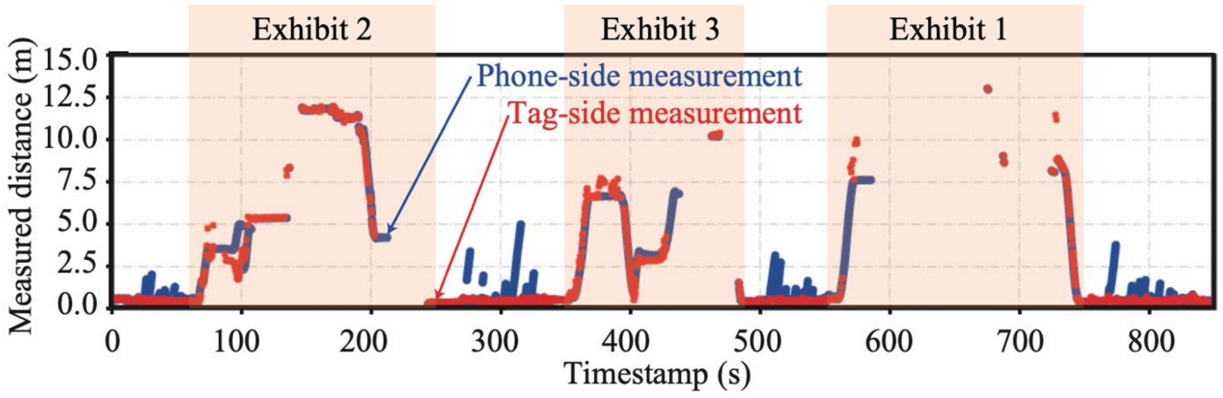


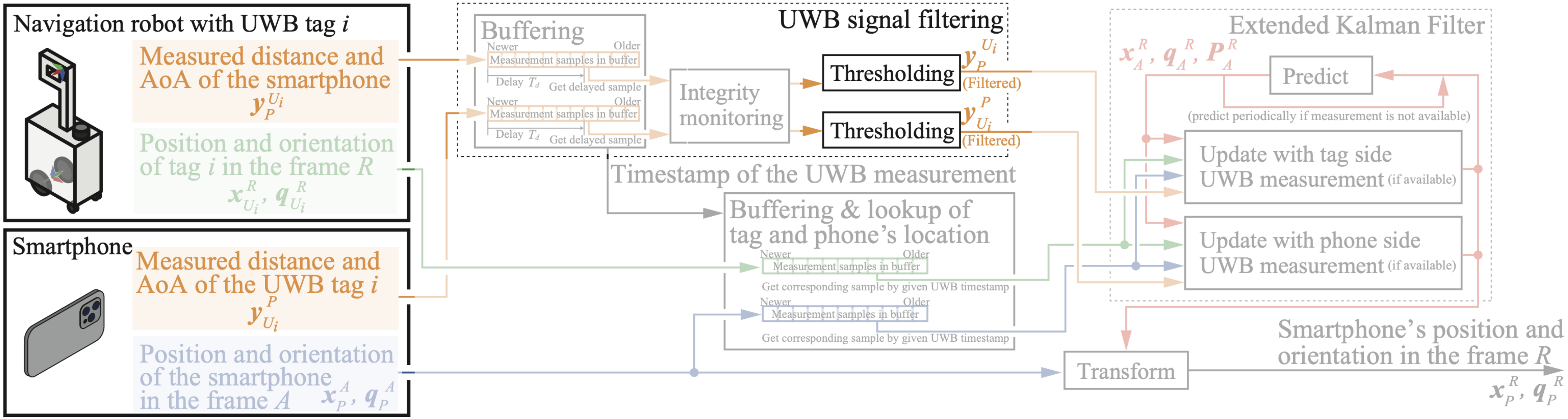
AoA : Angle of arrival
UWB: Ultra-wide band

Detail of UWB signal filtering (2/3)

- **Range and AoA thresholding**
  - check if the range & AoA are in a certain range (5.0 m, ±50 deg)
  - Max range: approx. 15 m, ±84 deg.
  - Far distance -> prone to AoA error.

Example of a measurement result



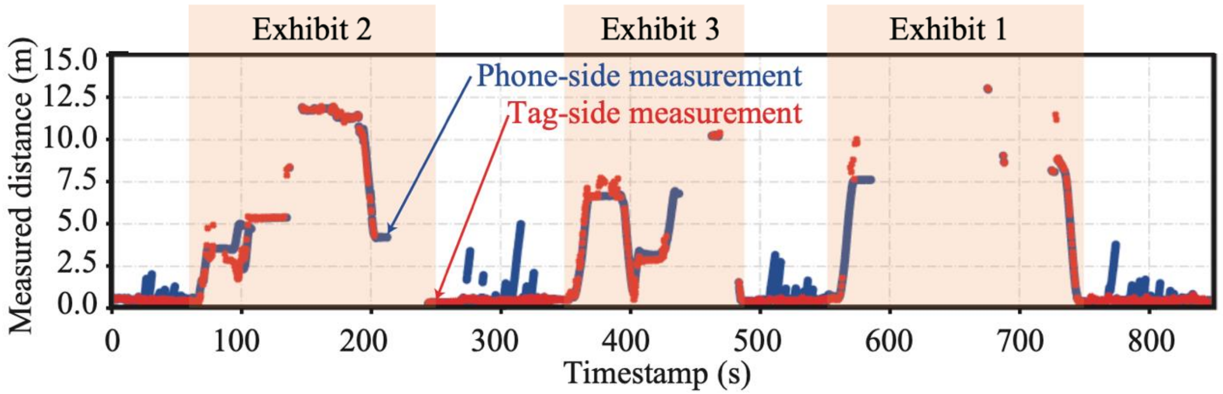


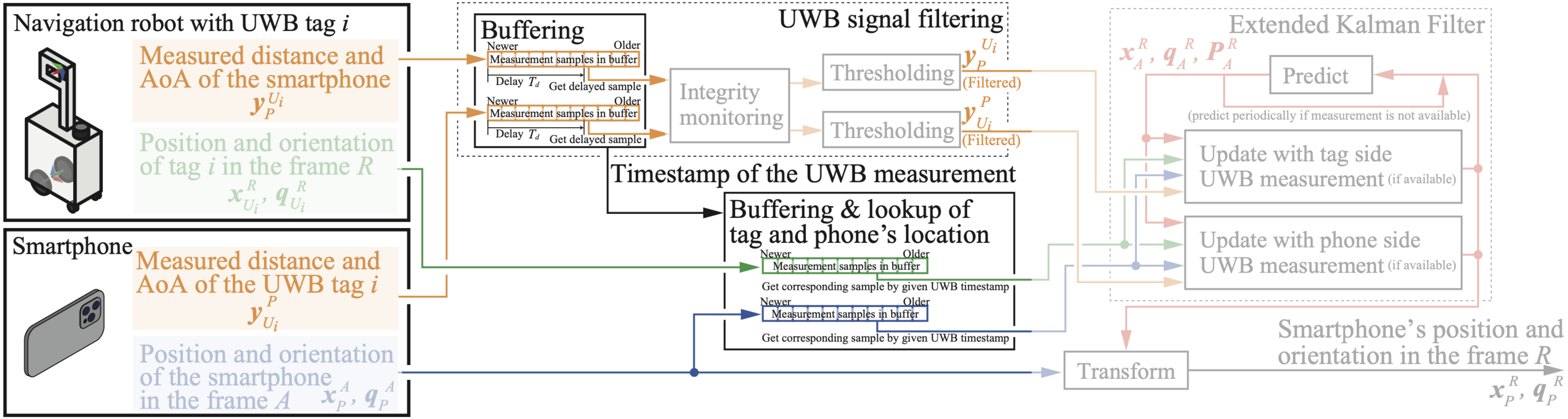
AoA : Angle of arrival
UWB: Ultra-wide band

Detail of UWB signal filtering (3/3)

- **Buffering and delayed evaluation**
  - UWB signal at start/end of continuous measurement is relatively noisy
  - Tag's position (=robot position) is obtained with delay (order of 0.1 s)
  - We intentionally evaluate UWB with delay (2 s)
  - Only delayed estimation for the VIO origin: no big problem unless VIO drifts fast

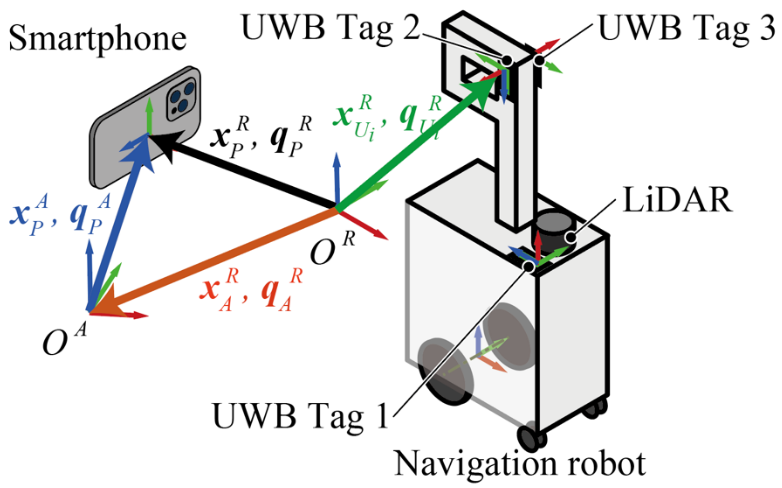
Example of a measurement result



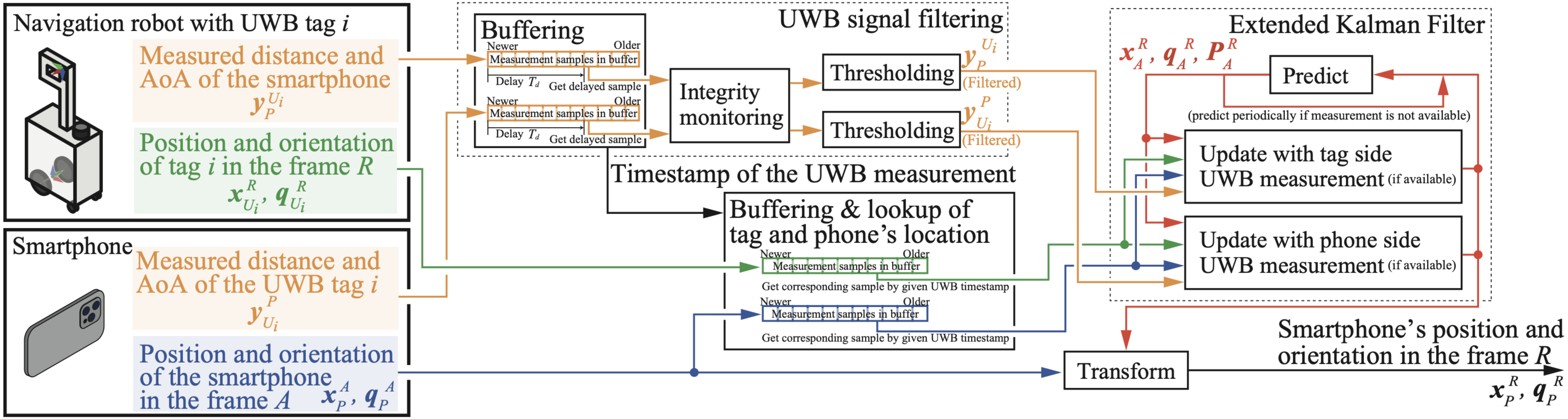


AoA : Angle of arrival
UWB: Ultra-wide band

Overview of the proposed method (Repost)



- The proposed method estimates the smartphone's location and orientation in the frame R (global frame)
- Proposed method consists of UWB signal filter, extended Kalman filter and transformation



AoA : Angle of arrival
UWB: Ultra-wide band

Experimental condition - Overview

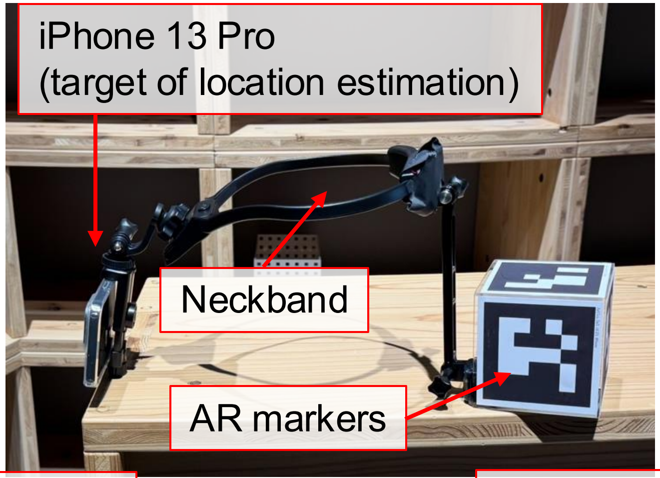
- Measure sensor data with mock tours in a museum
  - 15 to 30 minutes per tour
  - 2 to 6 tours per participant
- Participants were asked to
  - Wear smartphone & AR markers on the neck
  - Hold navigation robot and walk as the robot moves
  - Move without navigation robot based on a narrator’s voice
  - Touch the exhibits to experience them
- Participants
  - 2 people with visual impairment
  - 4 people without visual impairment
- Evaluation
  - Ground truth: AR markers with another camera-equipped mobile robot
  - 2D and 3D location errors

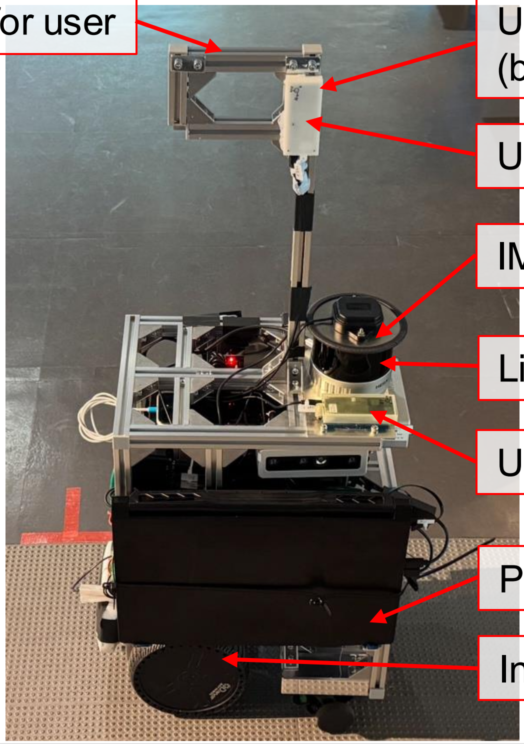
IRB number: HF2024-1438

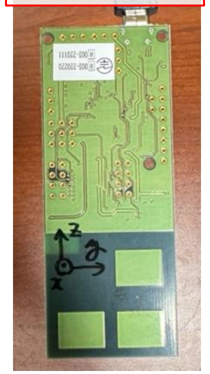
AoA : Angle of arrival
UWB: Ultra-wide band

Experimental condition - Equipment

- Smartphone (iPhone 13 Pro, Apple)
  - Hanged at the neck of subjects
  - Equipped with AR markers for ground truth
  - Sends sensor data (VIO (ARKit) , IMU, UWB) to the navigation robot with MQTT over WiFi
  - UWB: without camera-assistance features
- Navigation robot (AI Suitcase)
  - LiDAR (XT-16, Hesai) and IMU (BNO055, Bosch) for localization in a pre-built 2D floor map
  - UWB tags (Type 2BP development kit, Murata)
  - Personal Computer (PC)
  - Remote controlled by an experimenter
    - Pulls user’s hand toward destinations



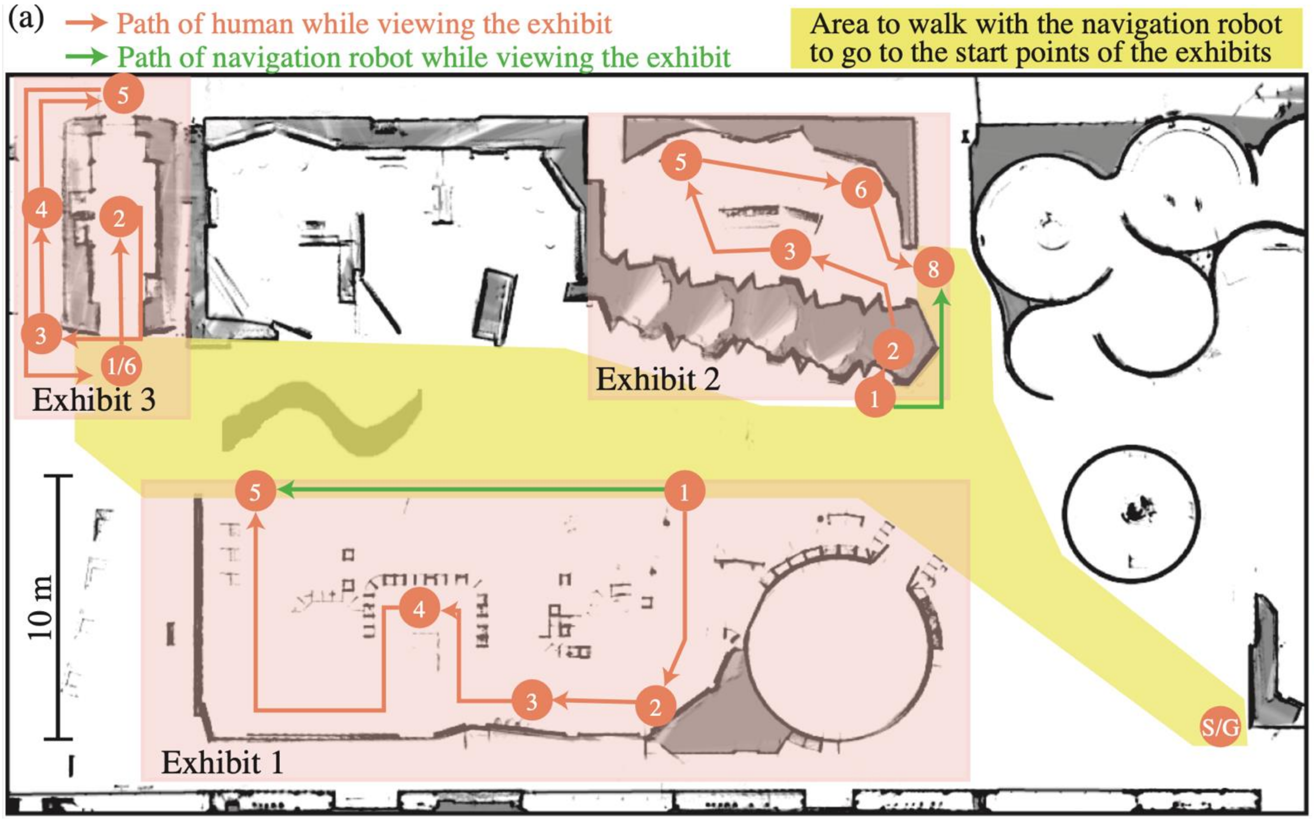


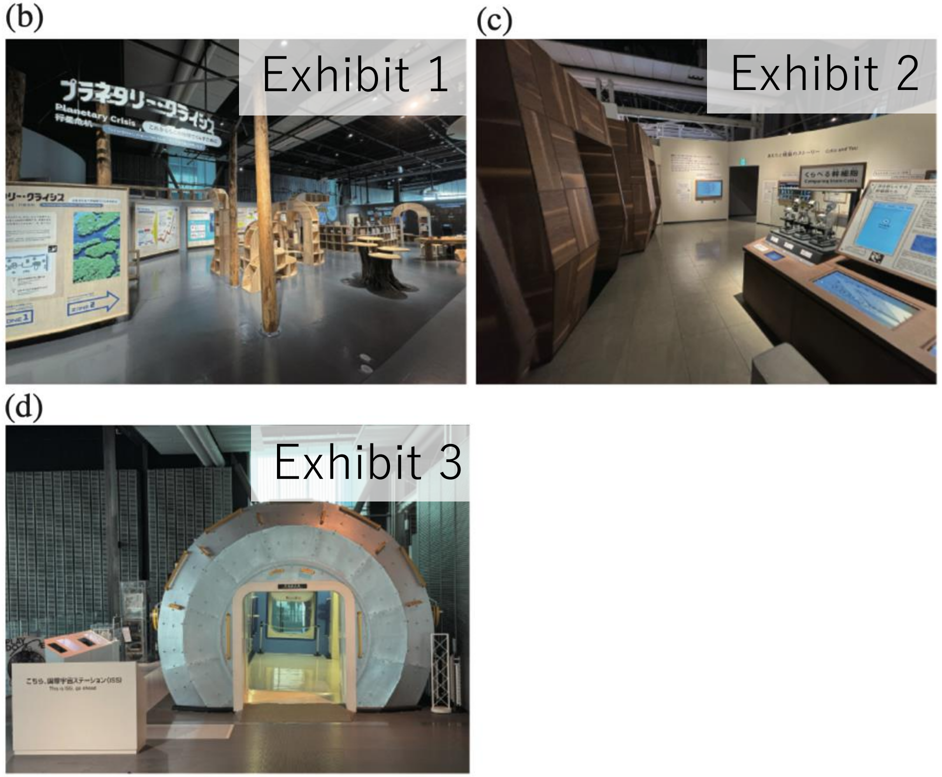


VIO: Visual-inertial odometry
MQTT: Message Queuing Telemetry Transport
IMU : Inertial measurement unit
LiDAR: Light detection and ranging
AoA : Angle of arrival
UWB: Ultra-wide band

Experimental condition - Venue and paths

- Miraikan - The National Museum of Emerging Science and Innovation
- 5th floor, following 3 exhibits
  - Exhibit 1: Relatively open space
  - Exhibit 2: Small room with curtains at the start
  - Exhibit 3: Mockup of international space station module, made of metal

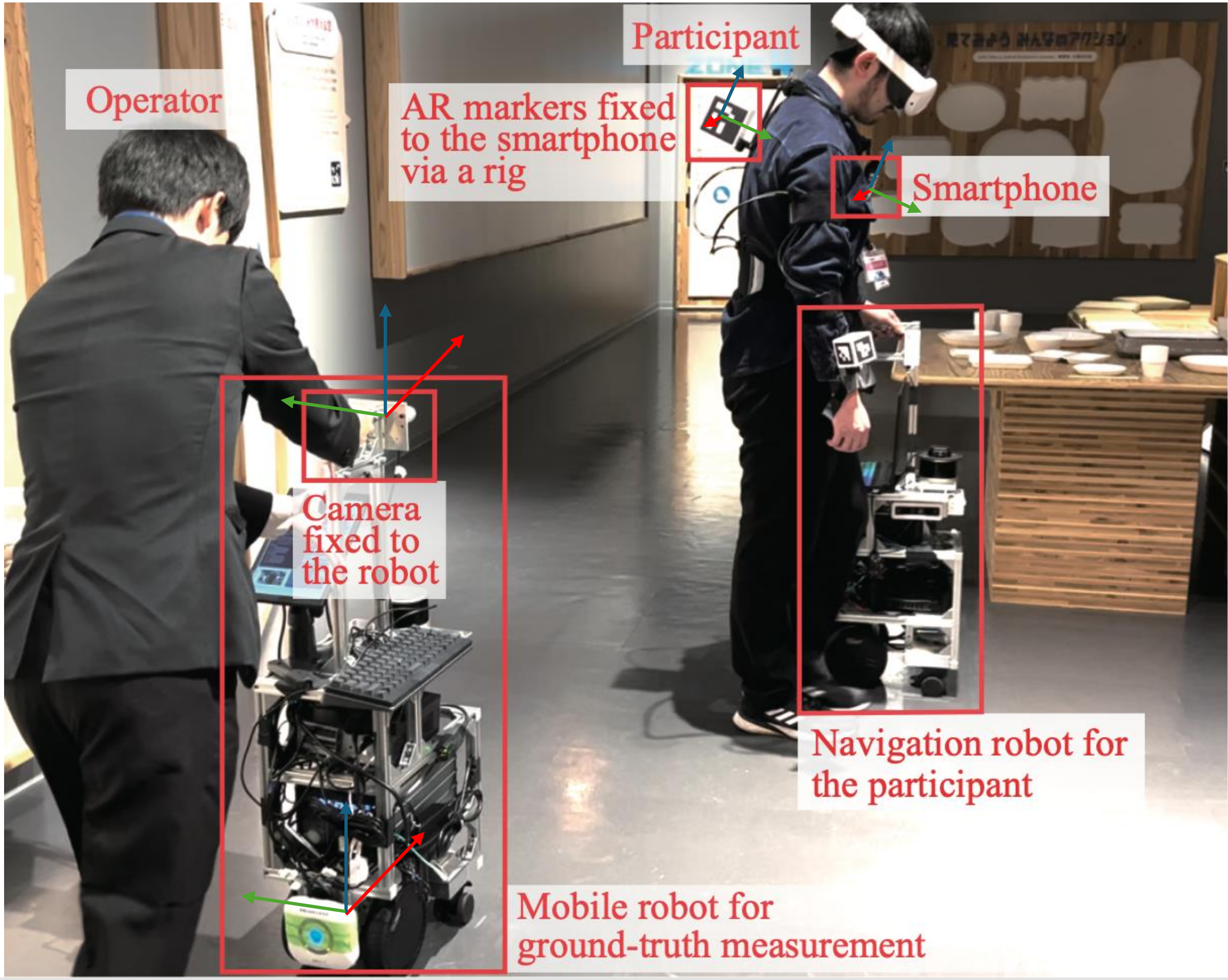




IRB number: HF2024-1438

Method to measure ground truth

- Measure sensor data with best-effort ground truth
  - AR markers at the neck
  - Another mobile robot tracks markers
  - AR markers on 5-faces of a cube
- Only for ground truth & evaluation
  - Proposed method do not use this information in estimation

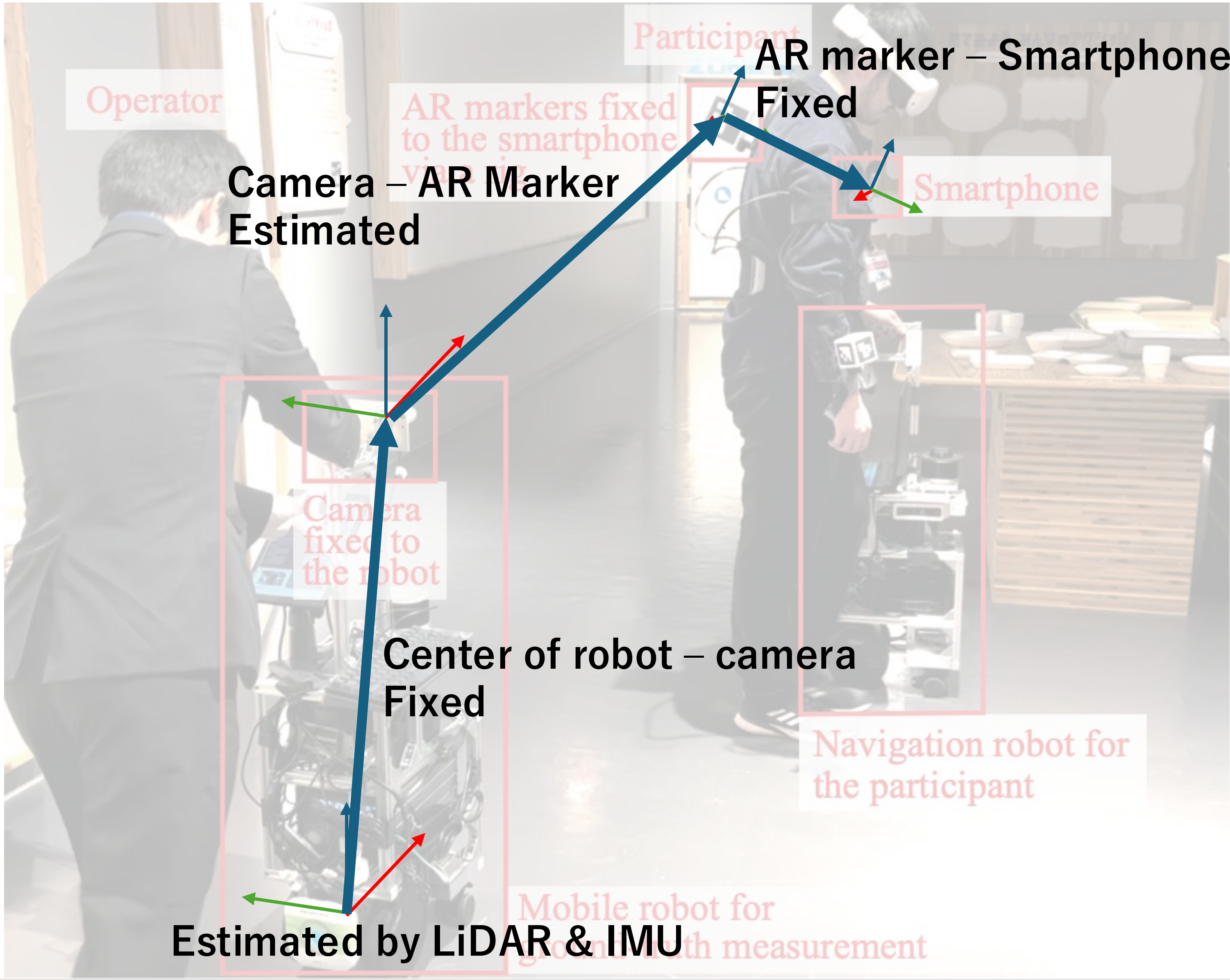


IRB number: HF2024-1438

IMU : Inertial measurement unit
LiDAR: Light detection and ranging

Method to measure ground truth

- Measure sensor data with best-effort ground truth
  - AR markers at the neck
  - Another mobile robot tracks markers
  - AR markers on 5-faces of a cube
- Only for ground truth & evaluation
  - Proposed method do not use this information in estimation



IMU : Inertial measurement unit
LiDAR: Light detection and ranging

IRB number: HF2024-1438

Experimental condition - Baseline

- Comparison with VIO-only results and using UWB/Robot
  - However, VIO-only is not feasible in the real situation (only relative location)
- Mocks the visual-inertial odometry system that aligns the origin at the first time.

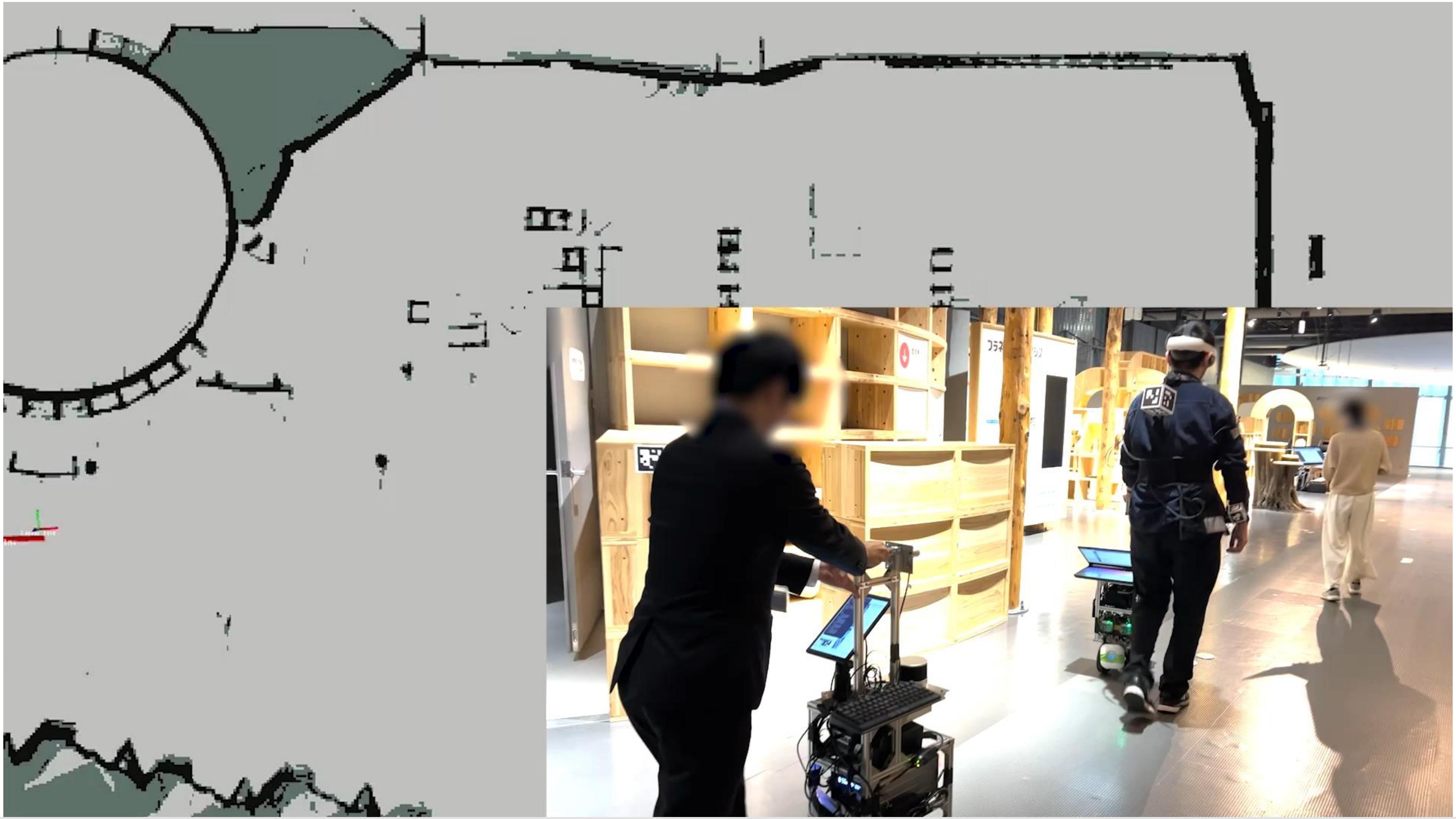
	Estimated states	Use visual-inertial odometry?	Use UWB (range + AoA)?	Use the robot's location and orientation?	Use the ground truth? (not available in real use cases)
Proposed	**Origin of VIO (x, y, z, yaw)**	**Yes**	**Yes**	**Yes**	No
Baseline	**Origin of VIO (x, y, z, yaw)**	**Yes**	No	No	**Use for first 30 seconds of walk**

IRB number: HF2024-1438

VIO: Visual-inertial odometry

AoA : Angle of arrival
UWB: Ultra-wide band

Example of localization

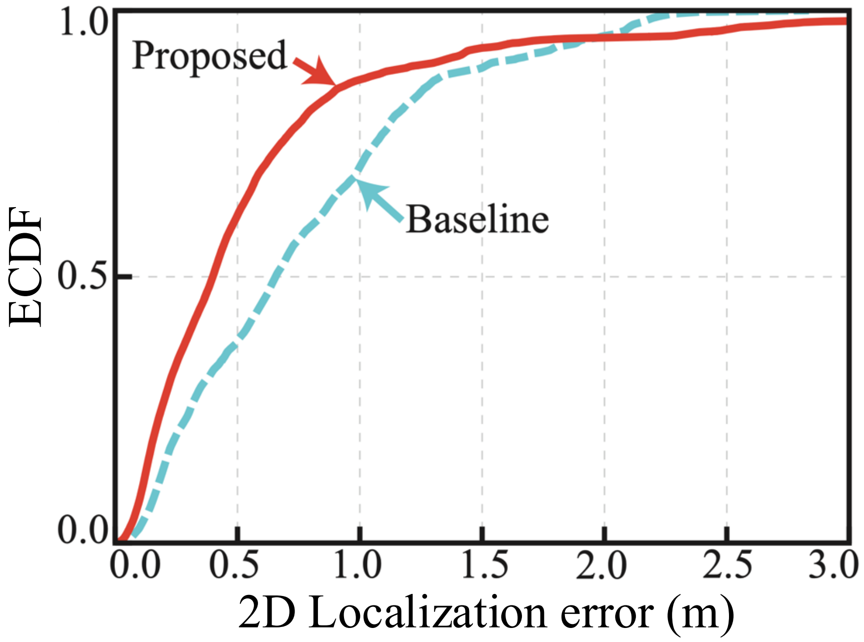


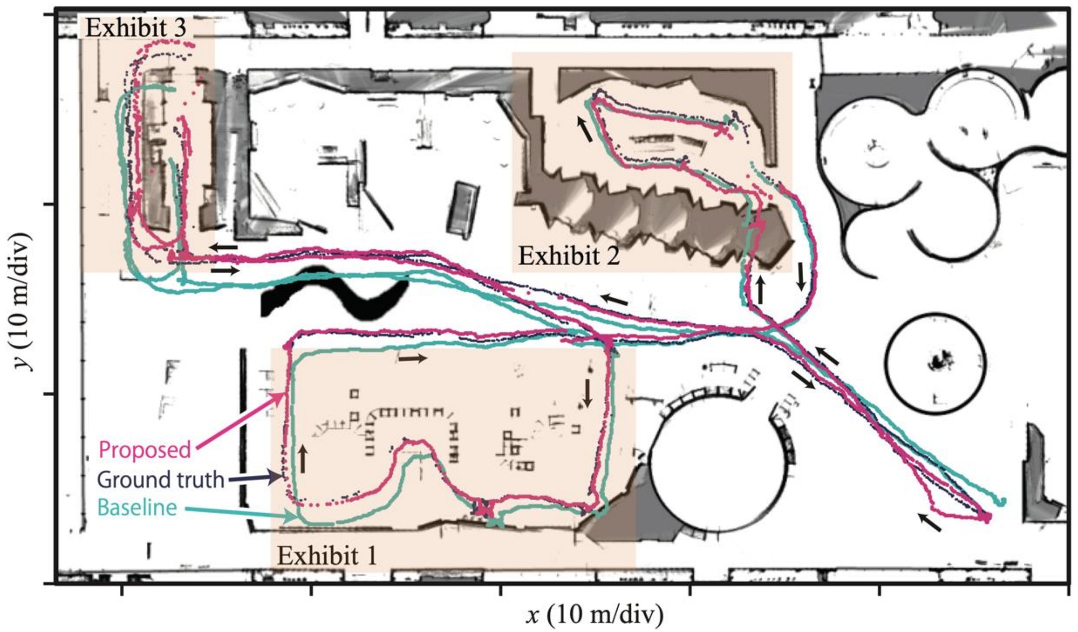
IRB number: HF2024-1438

Results

- Proposed method have better performance under approx. 90 percentile
- Baseline gives better performance not having outliers
  - Baseline uses ground truth + batch processing
    → Does not have initialization phase

Results for all paths with 6 subjects (139 min in total)



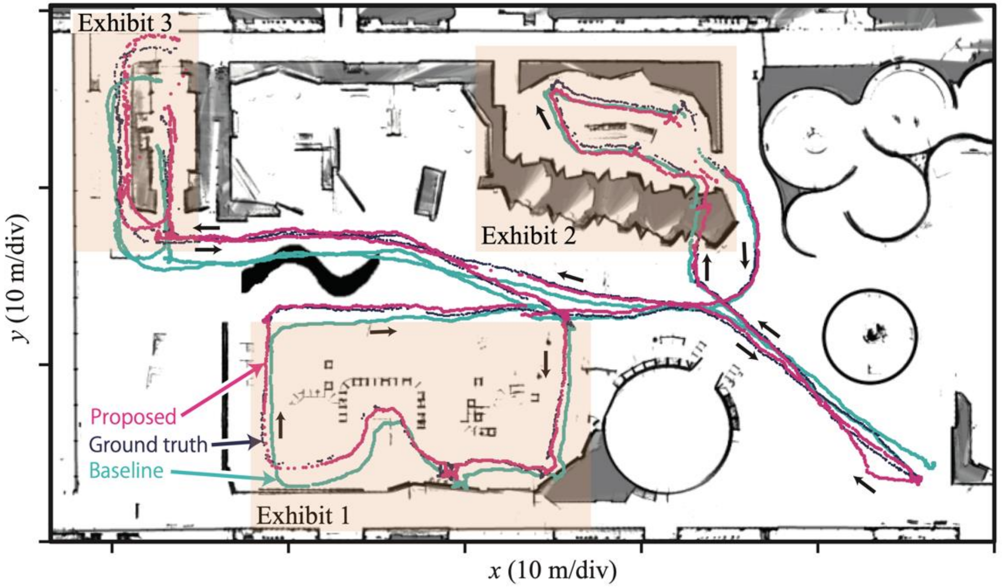


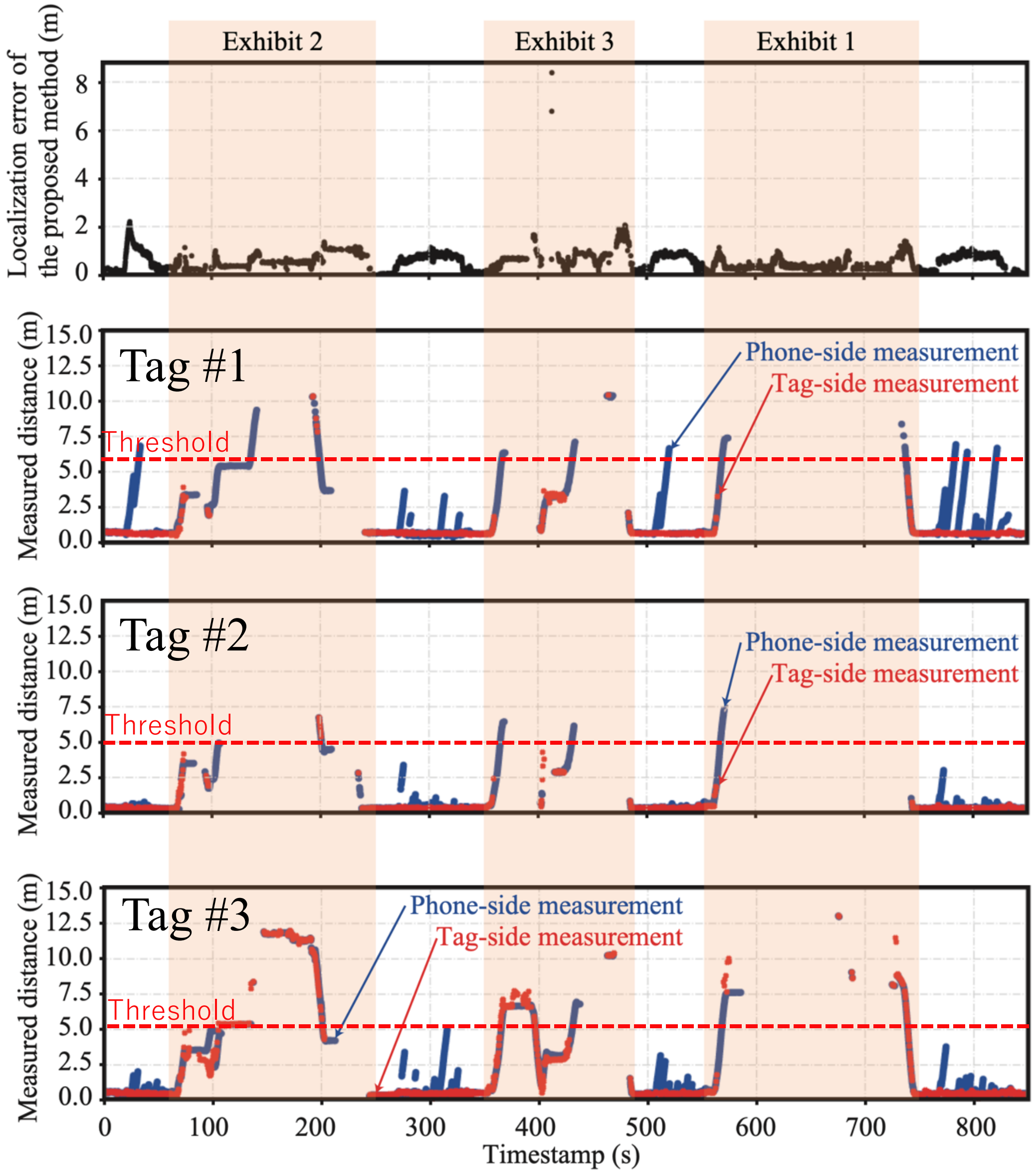
	2D error (m)			3D error (m)		
	Median	Mean	90%tile	Median	Mean	90%tile
Proposed	**0.40**	**0.58**	**1.28**	**0.42**	**0.60**	**1.29**
Baseline	0.65	0.76	1.53	0.67	0.79	1.56

VIO: Visual-inertial odometry ECDF: Empirical cumulative distribution function

Discussions

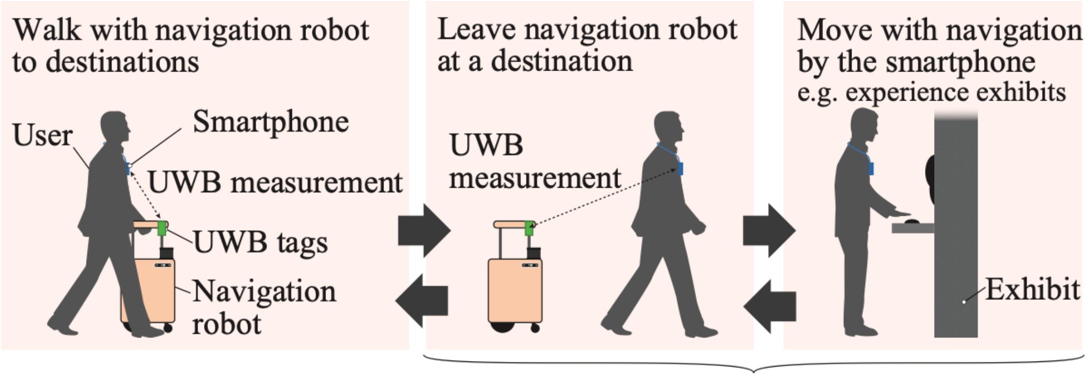
- Cause of location error?
  - Initial heading error
    - First movement fixes the heading
  - Misalignment when departing from the navigation robot
    - Hearing misalignment affects in far-side of exhibits
  - Long period of UWB absence
    - Larger covariance in EKF -> prone to outliers





Conclusions

Acknowledgement : This paper is based on results obtained from a project, Programs for Bridging the gap between R&D and the IDeal society (society 5.0) and Generating Economic and social value (BRIDGE)/Practical Global Research in the AI × Robotics Services, implemented by the Cabinet Office, Government of Japan.
The authors thank the participants, the staffs at Miraikan and the staffs at AIST for their cooperation in this experiment.



The proposed localization method is for navigation in these phases

- **Purpose**
  - Smartphone's localization in sub-meter accuracy without additional infrastructural investment & maintenance
- **Approach**
  - Estimate the smartphone's location by utilizing a navigation robot as a reference point using relative position measurement by UWB
- **Experiment**
  - Collected data in a museum with dummy tours with 6 participants (2 people with VI, 4 people without VI)
  - 139 minutes in total
- **Results & Discussions**
  - Proposed method achieved median error of 0.4 m, which achieves the objective (sub-meter)
  - Initial heading, misalignment at the departure and UWB reception after a long absence may cause error in the proposed method.
- **Conclusions**
  - Achieved sub-meter accuracy (0.4 m in median) without additional infrastructure to the facility or additional maps.
- **Future works**
  - Build and evaluate navigation system using the proposed method
  - Enhance UWB filtering method
  - Batch optimization for origin estimation
  - **Localization competition will start in June**

Preparing a competition using sensor data in this work

VI: Visual impairment
UWB: Ultra-wide band

Competition (announcement)

- We are going to release the dataset & enhanced evaluation tools for a localization competition
- The detail will be released in June. Please bookmark the web page.

Competition site