UHead: Driver Attention Monitoring System Using UWB Radar

Chongzhi Xu, Xiaolong Zheng, Zhiyuan Ren,
Liang Liu, Huadong Ma

Beijing University of Posts and Telecommunications

汇报人：1024040912张婷婷

Xiaolong Zheng | 郑霄龙

Conference Papers

1. [ICC'25] Enabling Cross Medium Communication with Passive Relay
   Hengbin Wang, Dan Xia, Peichen Zhao, Liang Liu, Huadong Ma, **Xiaolong Zheng***
   IEEE International Conference on Communications, Montreal, Canada, June 8-12, 2025.
2. [INFOCOM'25] Enabling Reliable LoRa Decoding under Cross-channel Interference
   Fu Yu, **Xiaolong Zheng***, Dan Xia, Liang Liu, Huadong Ma
   IEEE International Conference on Computer Communications, London, United Kingdom, May 19-22, 2025.
3. [MSN'24] Enable Online LoRa Decoding under Partially Overlapping Interference
   Yuhao Ma, Fu Yu, **Xiaolong Zheng***, Liang Liu, Huadong Ma
   IEEE International Conference on Mobility, Sensing and Networking (MSN 2024), Harbin, China, December 20-22, 2024.
4. [MSN'24] MAWI:Metasurface Aided WiFi Imaging
   Leiyang Xu, **Xiaolong Zheng***, Huiming Yao, Liang Liu
   IEEE International Conference on Mobility, Sensing and Networking (MSN 2024), Harbin, China, December 20-22, 2024.
5. [MobiCom'24] Plug-and-play Indoor GPS Positioning System with the Assistance of Optically Transparent Metasurfaces (PDF)
   Ruinan Li, **Xiaolong Zheng***, Liang Liu, Huadong Ma
   The 30th Annual International Conference On Mobile Computing And Networking (MobiCom 2024), Washington, D.C., USA, November 18-22, 2024.

Journal Articles/Book Chapters

1. [TON] Improving Data Collection Efficiency of UAV-assisted LoRa Networks via Directivity-aware Link Model
   Jiaqi Zhang, **Xiaolong Zheng***, Ruinan Li, Liang Liu, Huadong Ma*, Nei Kato
   IEEE/ACM Transactions on Networking, accepted.
2. [TMC] WiCamera: Vortex Electromagnetic Wave-Based WiFi Imaging (PDF)
   Leiyang Xu, **Xiaolong Zheng***, Xinrun Du, Liang Liu*, Huadong Ma
   IEEE Transactions on Mobile Computing, accepted.
3. [CJE] Vortex EM Wave-Based Rotation Speed Monitoring on Commodity WiFi (PDF)
   Leiyang Xu, **Xiaolong Zheng***, Liang Liu*
   Chinese Journal of Electronics, accepted.
4. [TMC] LoRadar: An Efficient LoRa Channel Occupancy Acquirer based on Cross-channel Scanning (PDF)
   Xiaolong Zheng, Fu Yu, Liang Liu, Huadong Ma
   IEEE Transactions on Mobile Computing, vol. 24, no. 3, pp. 1699-1714, March 2025.
5. [COMST] Wireless Sensing for Material Identification: A Survey (PDF)
   Yande Chen, Chongzhi Xu, Kexin Li, Jia Zhang, Xiuzhen Guo, Meng Jin, **Xiaolong Zheng**, Yuan He
   IEEE Communications Surveys & Tutorials, accepted.

Huadong Ma

Also published under: H. Ma, Hua-Dong Ma

Affiliation

School of Computer Science (National Pilot Software Engineering School)
Beijing University of Posts and Telecommunications
Beijing, China

Publication Topics

Deep Reinforcement Learning, Neural Network, Deep Learning, Feature Maps, Attention Mechanism, Convolutional Neural Network, Internet Of Things, Convolutional Layers, Markov Decision Process, Packet Loss, Real-world Data, Real-world Datasets

Show More

Biography

Huadong Ma (Fellow, IEEE) received the B.S. degree in mathematics from Henan Normal University, Xinxiang, China, in 1984, the M.S. degree in computer science from the Shenyang Institute of Computing Technology, Chinese Academy of Sciences, Beijing, China, in 1990, and the Ph.D. degree in computer science from the Institute of Computing Technology, Chinese Academy of Sciences, in 1995. From 1999 to 2000, he held a visiting position with the University of Michigan, Ann Arbor, MI, USA. He is currently a Professor and the Executive Dean of the School of Computer Science, Beijing University of Posts and Telecommunications, Beijing. He has published more than 300 papers in journals, such as ACM/IEEE Transactions or conferences, such as ACM MobiCom/MM, IEEE INFOCOM, ACM SIGCOMM, and five books. His current research interests include the Internet of Things, sensor networks, and multimedia computing. He is an Editorial Board Member of the IEEE Transactions on Multimedia, the IEEE Internet of Things Journal, the ACM Transactions on Internet of Things, and the Multimedia Tools and Applications. He received the Natural Science Award from the Ministry of Education, China, in 2017. He received the 2019 Prize Paper Award from the IEEE Transactions on Multimedia, the 2018 Best Paper Award from the IEEE Multimedia, the Best Paper Award from IEEE ICPADS 2010, and the Best Student Paper Award from IEEE ICME 2016 for his coauthored papers. He received the National Funds for Distinguished Young Scientists in 2009. He serves as the Chair for ACM SIGMOBILE China. *(Based on document published on 23 June 2023).* Show Less

Driver Attention Monitoring

Enhance Driving Safety

- 90% of road accidents are closely related to distracted driving.

Enrich Driving Experience

- Combined with head-up display.
- Automotive headlight direction adjustment.

Existing Solutions

Wearable

- Physiological discomfort

Camera

- Vulnerable to light
- Privacy issue

Acoustic

- Contaminated by background noise

RF Sensing for Driver Attention Monitoring

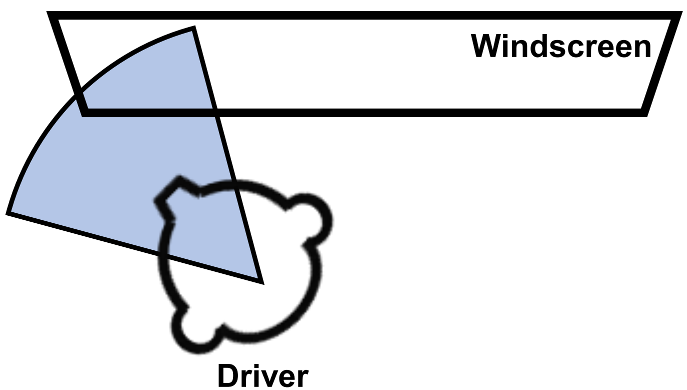
- Contactless and no privacy concerns
- Unaffected by light and background noise

UWB for driver attention monitoring on a phone holder in car.

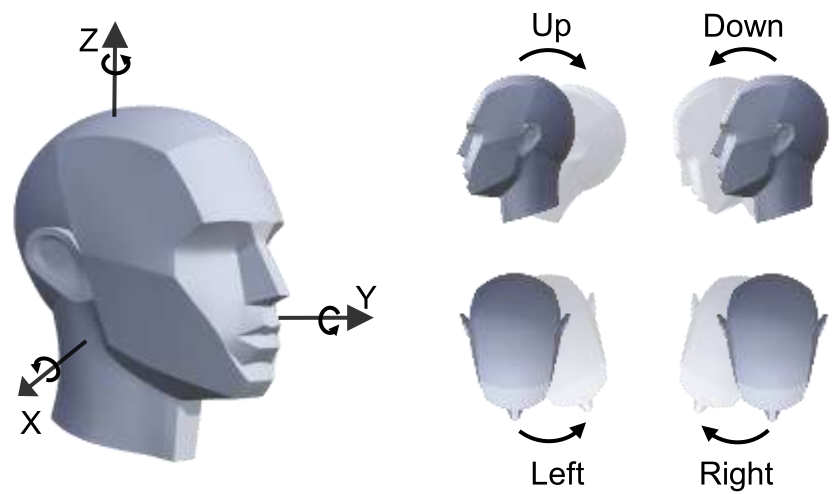
How to Monitor Driver Attention via UWB?

Head rotation is an indication of the driver's attention

- Head direction and driver attention are highly correlated.

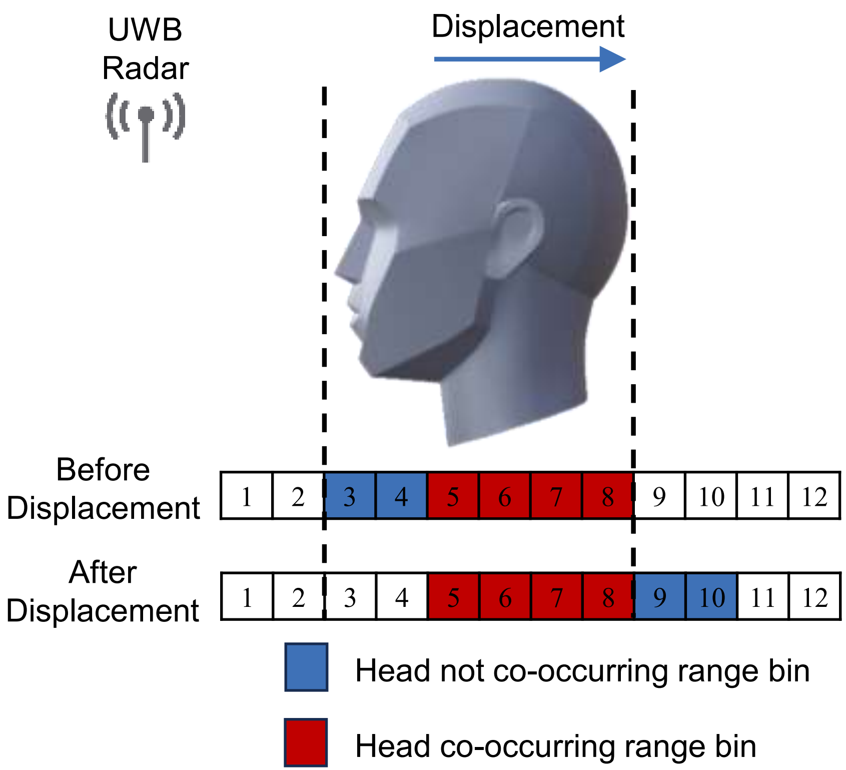


- Four directions of head rotation will affect driver's attention.

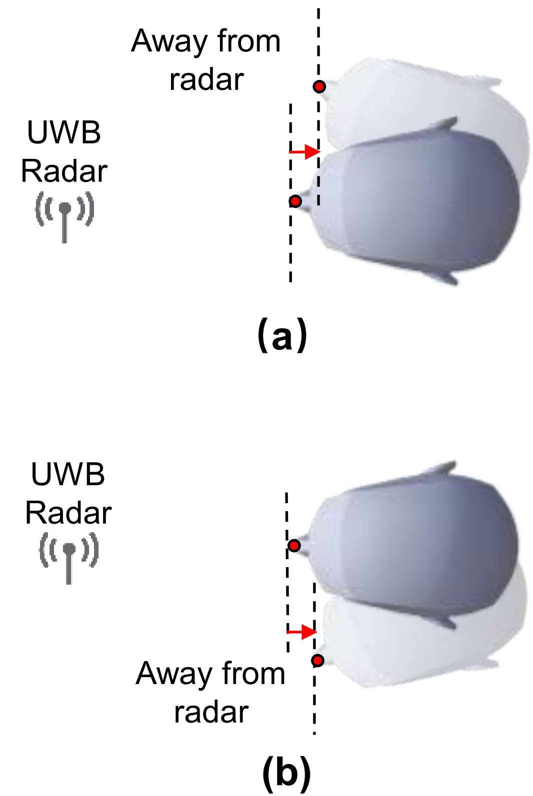


Rotation Direction Classification

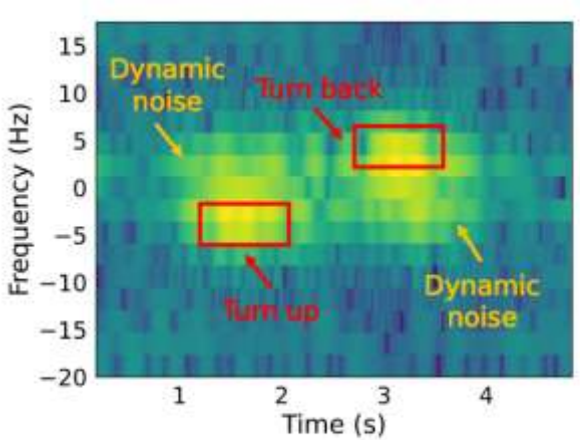
Driver Position Estimation



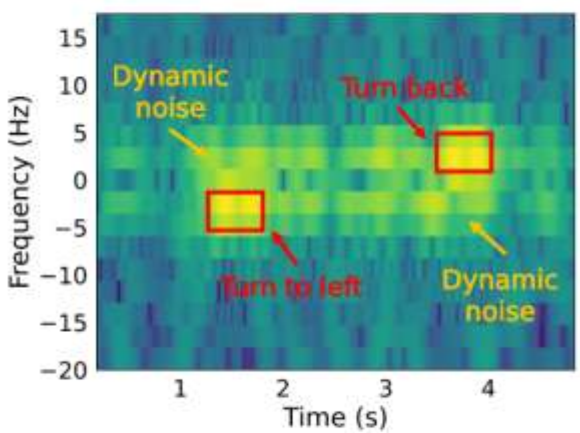
UWB Radar Location



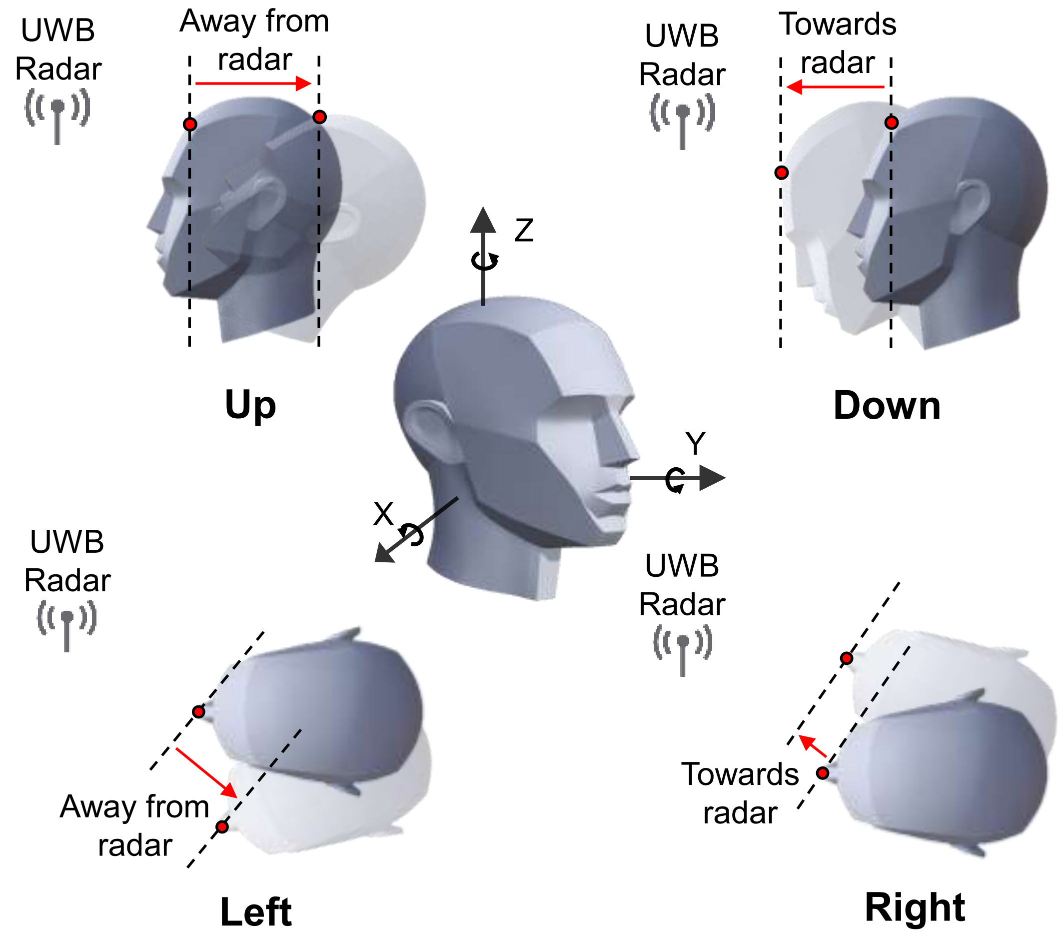
Rotation Direction Recognition



(a) Head rotation around X axis

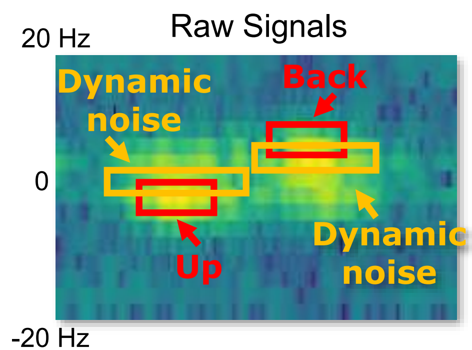


(b) Head rotation around Z axis



Head Rotation Doppler Profiles Extraction

C1: Rotation angle estimation relies on Doppler profiles, but in which head rotation information is coupled with dynamic noises.

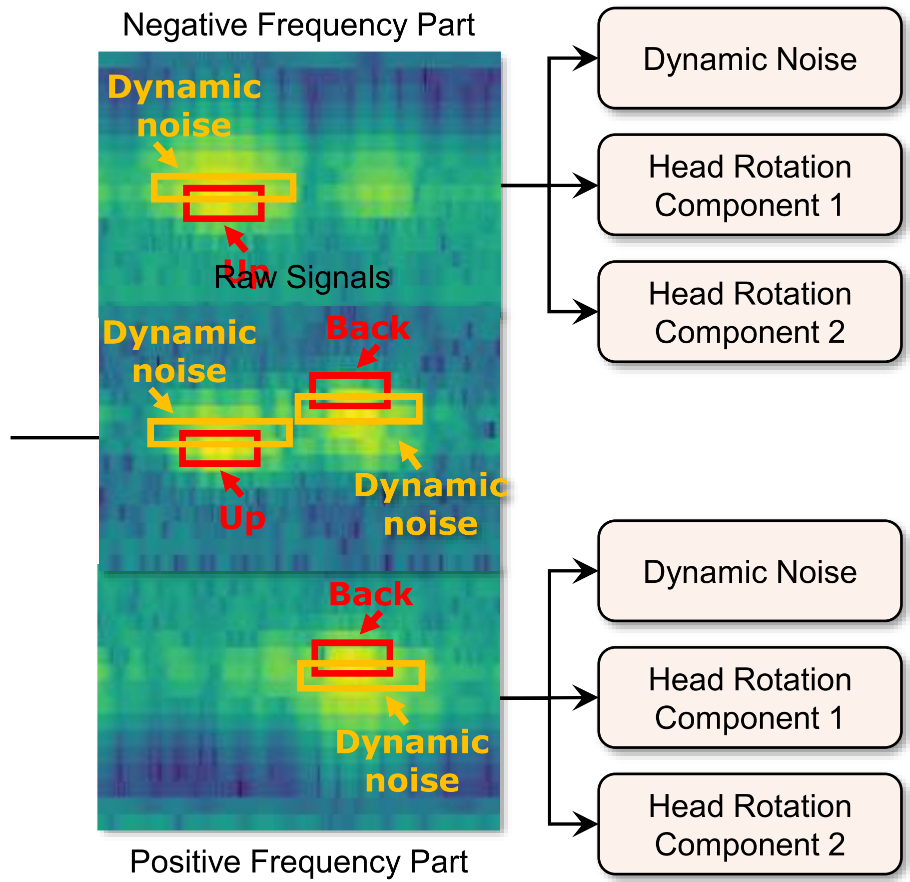


Dynamic noises: tiny body swing

- Temporal randomness
- Frequency coupled with head rotation

Head Rotation Doppler Profiles Extraction

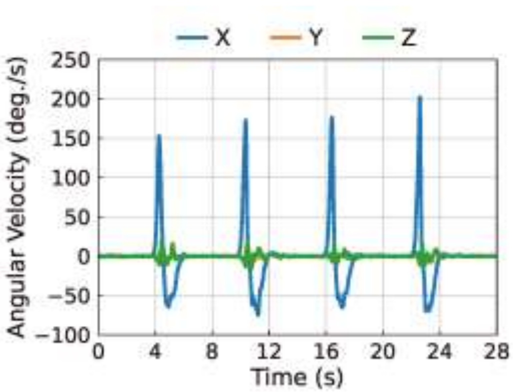
$$f_D = \frac{2f}{c} wr$$



High Resolution TF Representation

C2: Rotation angle estimation requires precise angular velocity, which causes Doppler shifts, but it is not constant in time.

$$f_D = \frac{2f}{c}\omega r$$

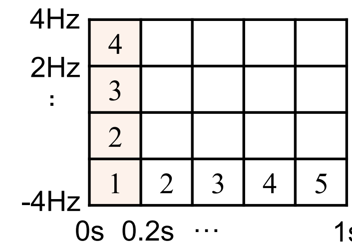


The trade-off of STFT: time and frequency resolution.

Window = 4 (small):
Time resolution =0.2 s **High**
Frequency resolution = 2 Hz

1	2	3	4	5	6	7	8

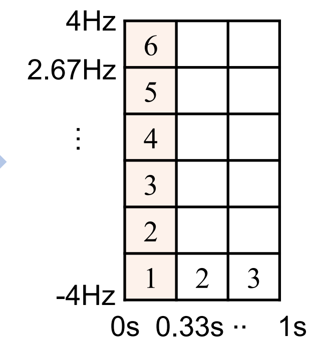
0s 1s



Window = 6 (large):
Time resolution =0.33 s
Frequency resolution = 1.33 Hz **High**

1	2	3	4	5	6	7	8

0s 1s



Note: TF Representation is Time-Frequency Representation

High Resolution TF Representation

STFT

$$STFT(t,\omega)=\int_{-\infty}^{\infty}s_n(\tau)\boxed{\omega(\tau-t)}e^{-j\omega\tau}d\tau$$

Wigner-Ville Distribution (WVD)

$$WVD_s(t,\omega)=\int_{-\infty}^{\infty}\underbrace{\boxed{s_n\left(t+\frac{\tau}{2}\right)s_n^*\left(t-\frac{\tau}{2}\right)}}_{R(t,\tau)}e^{-j\omega\tau}d\tau$$

$$=\int_{-\infty}^{\infty}\left[s_1\left(t+\frac{\tau}{2}\right)+s_2\left(t+\frac{\tau}{2}\right)\right]\cdot\left[s_1\left(t-\frac{\tau}{2}\right)+s_2\left(t-\frac{\tau}{2}\right)\right]^*e^{-j\omega\tau}\,d\tau$$

$$=W_{s_1}(t,\omega)+W_{s_2}(t,\omega)+\boxed{W_{s_1s_2}(\omega)+W_{s_2s_1}(\omega)}$$

Pseudo Wigner-Ville Distribution (PWVD)

$$PWVD_s(t,\omega)=\int_{-\infty}^{\infty}\boxed{h(\tau)}s\left(t+\frac{\tau}{2}\right)s^*\left(t-\frac{\tau}{2}\right)e^{-j\omega\tau}d\tau$$

High Resolution TF Representation

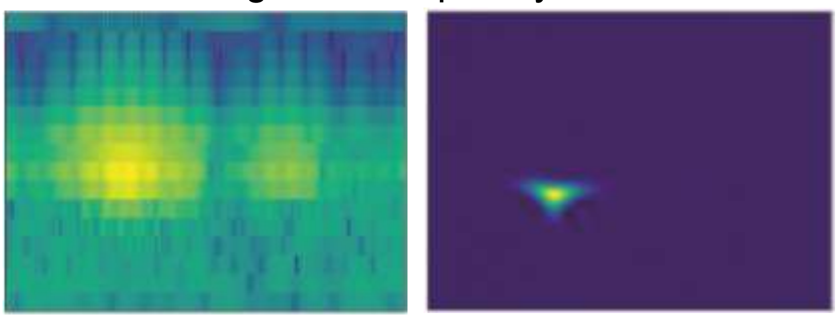
Pseudo Wigner-Ville Distribution (PWVD)

Instantaneous autocorrelation function

$$PWVD_s(t,\omega) = \int_{-\infty}^{\infty} \boxed{h(\tau)} \boxed{s\left(t+\frac{\tau}{2}\right) s^*\left(t-\frac{\tau}{2}\right)} e^{-j\omega\tau} d\tau$$

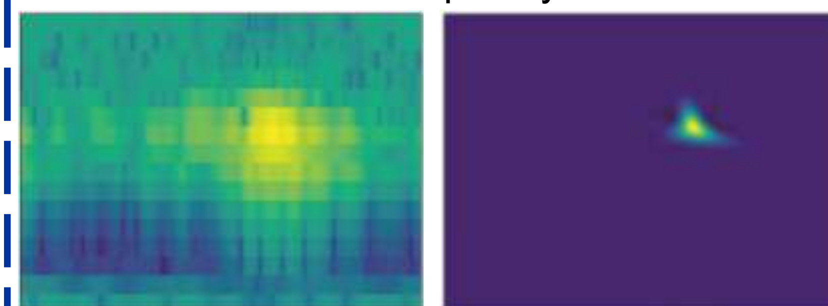
Hamming window

Negative Frequency Part



STFT PWVD

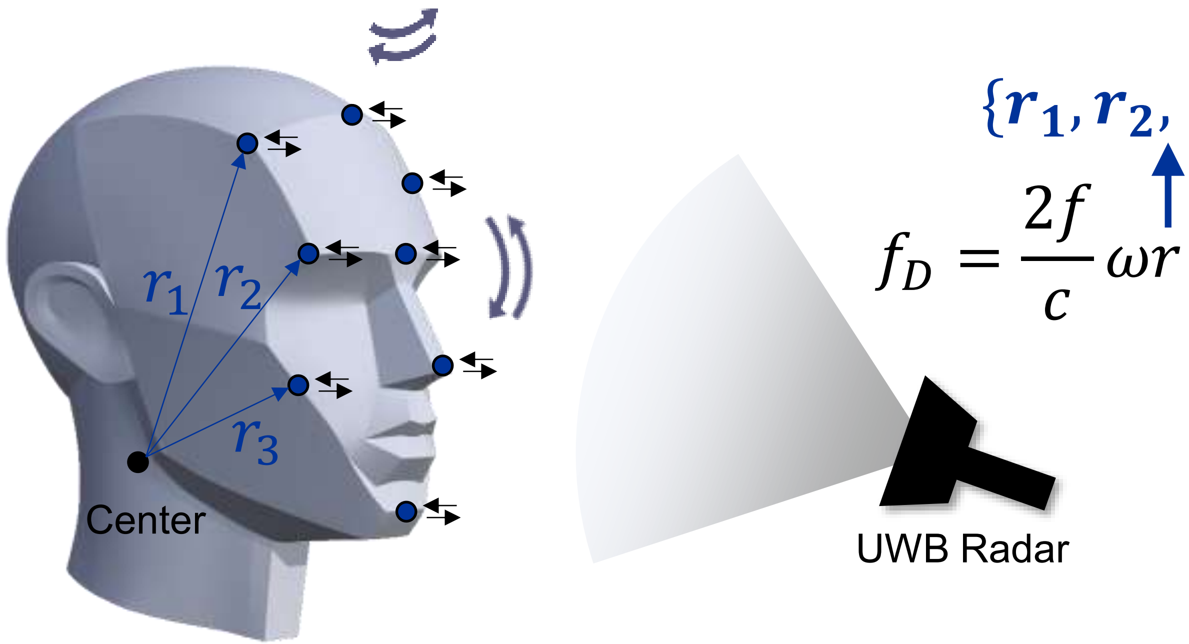
Positive Frequency Part



STFT PWVD

Head Rotation Angle Estimation

C3: Head rotation angle is hard to estimate because the signals from multiple reflection points on the head are coupled together.



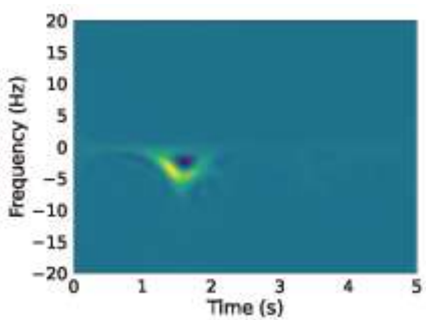
Head Rotation Angle Estimation

Head Structure-Based Rotation Angle Estimation Algorithm

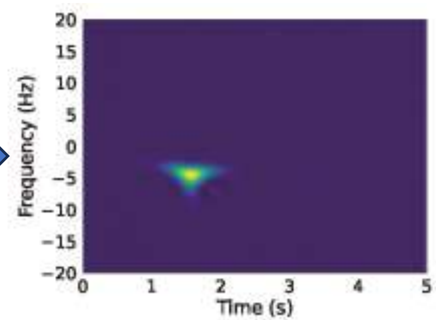
- Time-Frequency Representation Binarization
- Reflection Point Extraction
- Head Rotation Angle Estimation

Rotation Angle

$$S_D = \int \frac{2f}{c}\omega(t) r dt = \frac{2f}{c}\boxed{\theta} r$$

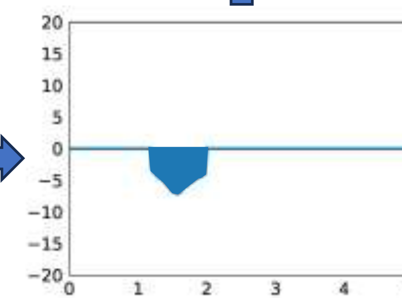


Negative frequency part



Remove dynamic noise


Binarization



Reflection point extraction

Experiment Setup

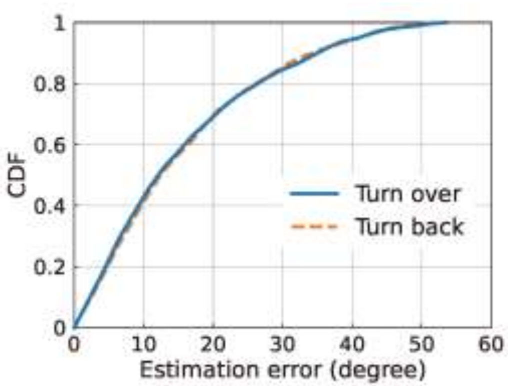
Novelda X4M05
UWB Radar

Experiment Settings

Overall Performance

$$r_x = 0.16m$$
$$r_z = 0.15m$$

Angle Estimation



Median error
Turn over: $12.59°$
Turn back: $12.96°$

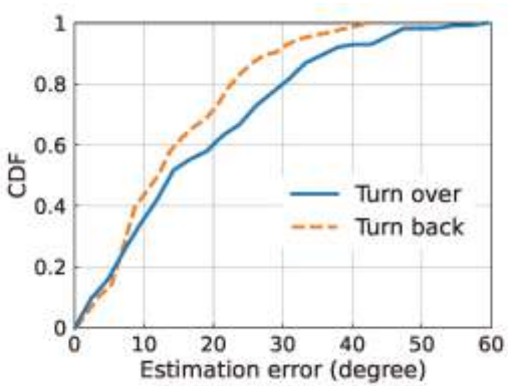
Direction Recognition

Test set

Cross person

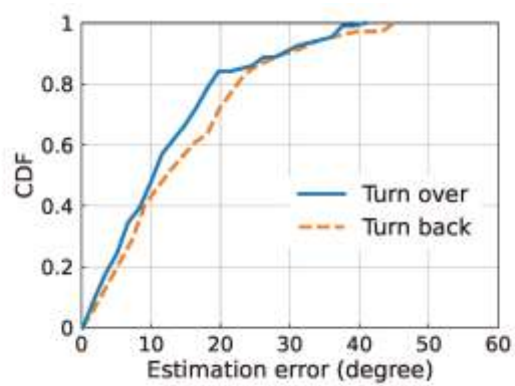
System Robustness

Road Bumps

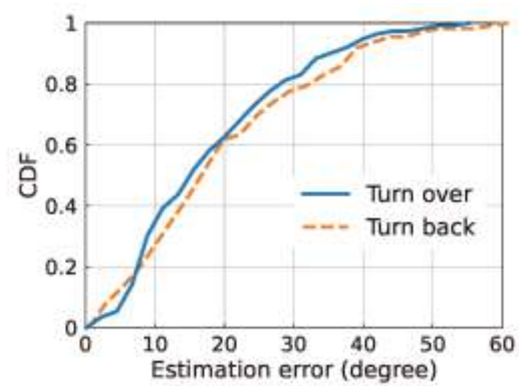


Median error
Turn over: $14.49°$
Turn back: $13.09°$

Presence of Passenger



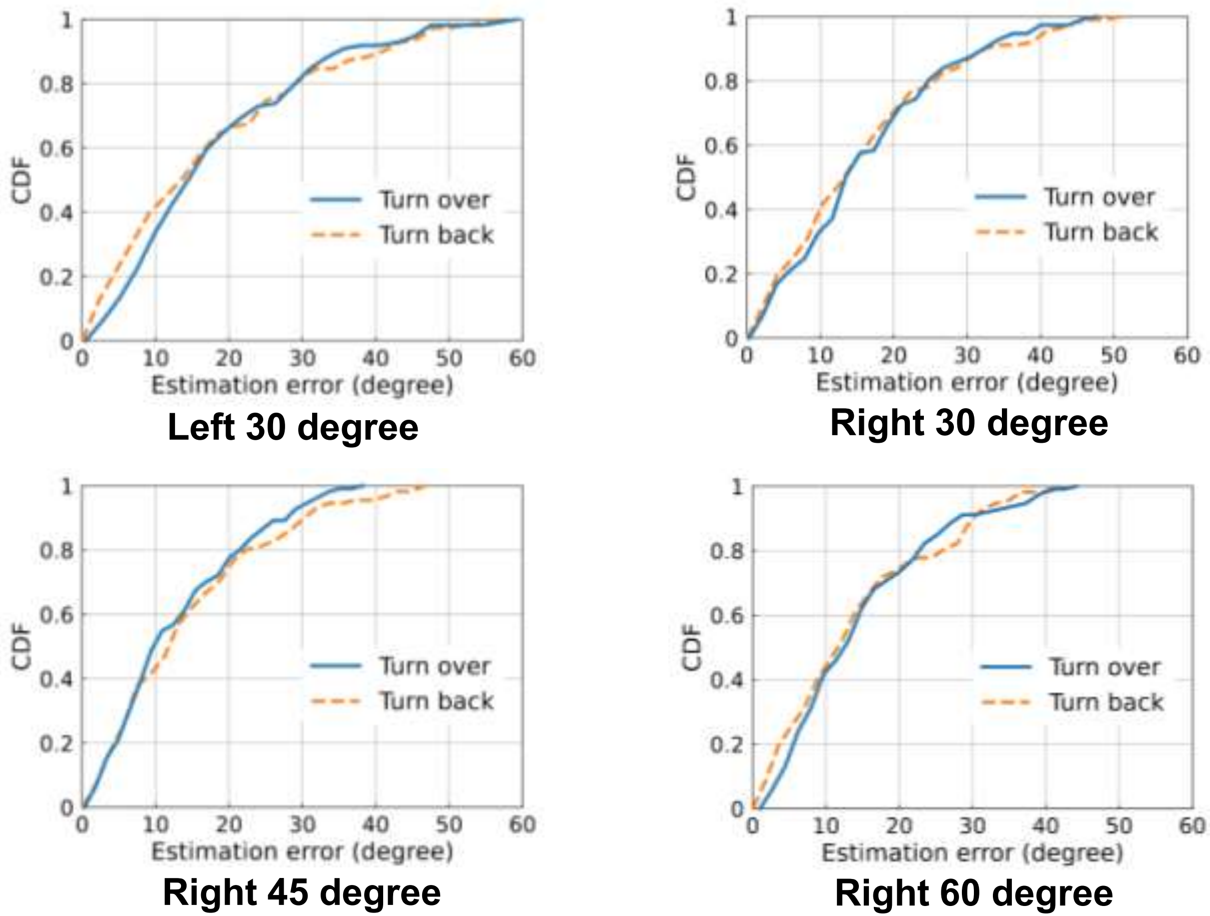
Rear



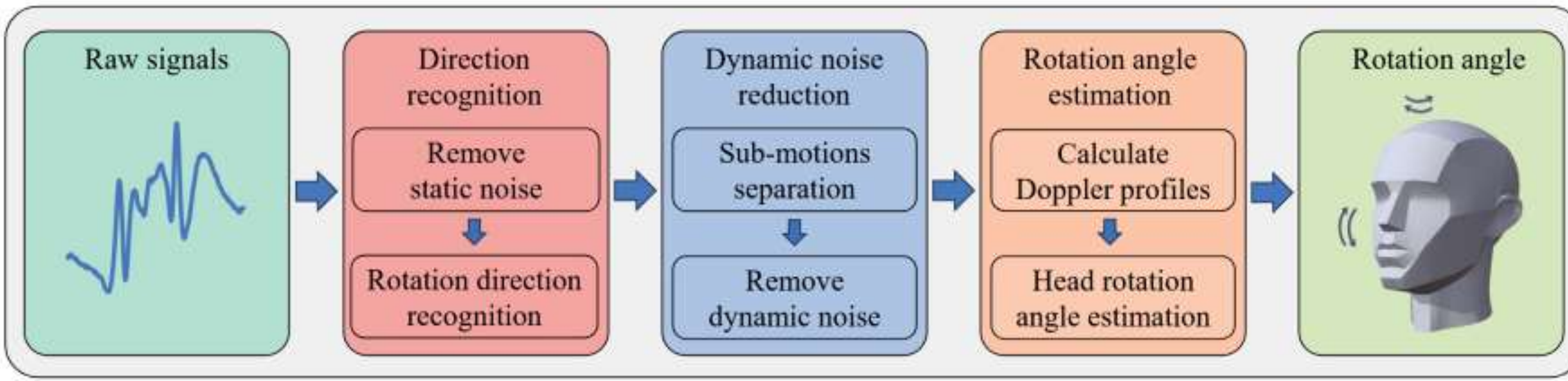
Copilot

System Robustness

Relative Locations of Radar



Conclusion



Raw signals
Direction recognition
Remove static noise
Rotation direction recognition
Dynamic noise reduction
Sub-motions separation
Remove dynamic noise
Rotation angle estimation
Calculate Doppler profiles
Head rotation angle estimation
Rotation angle

Thanks for listening!
Q&A

Complex Variational Mode Decomposition (CVMD)

（1）分离正负频率分量

- 对复信号 $s(t)$ 应用理想带通滤波器，分离出**正频率分量** $s_+(t)$ 和**负频率分量** $s_-(t)$：

$$B(e^{j\omega}) = \begin{cases} 1, & 0 \le \omega < \pi \\ 0, & -\pi \le \omega < 0 \end{cases}$$

  - $s_+(t)$ 包含正频率信息（如头部向雷达靠近的正多普勒频移）。
  - $s_-(t)$ 包含负频率信息（如头部远离雷达的负多普勒频移）。

（2）解析信号生成

- 将实信号转换为解析信号，保留单边频谱：

  $$m_k^+(t) = \left(\delta(t) + \frac{j}{\pi t}\right) * m_k(t)$$

  其中 $m_k(t)$ 是分解后的子信号，$\delta(t)$ 是狄拉克函数，确保频谱单边化。

（3）变分问题构造

- 目标：将信号分解为 K 个**本征模态函数（IMF）**，每个 IMF 围绕中心频率 ω_k，且带宽最小化。
- 约束条件：分解后的子信号之和等于原信号 $f(t)$。
- 优化问题：

  $$\min_{\{m_k\},\{\omega_k\}} \sum_{k=1}^{K} \left\| \partial_t \left[m_k^+(t) e^{-j\omega_k t} \right] \right\|_2^2, \quad \text{s.t.} \sum_{k=1}^{K} m_k(t) = f(t)$$

  其中 ∂_t 表示时间导数，通过最小化导数的范数来约束带宽。

Complex Variational Mode Decomposition (CVMD)

(4) 拉格朗日乘数法与 ADMM 求解

- 引入拉格朗日乘数 $\lambda(t)$ 和二次惩罚项，构造增广拉格朗日函数：

$$\mathcal{L} = \alpha \sum_{k=1}^{K} \left\| \partial_t \left[m_k^+(t) e^{-j\omega_k t} \right] \right\|_2^2 + \left\| f(t) - \sum_{k=1}^{K} m_k(t) \right\|_2^2 + \left\langle \lambda(t), f(t) - \sum_{k=1}^{K} m_k(t) \right\rangle$$

  - α 平衡数据保真度与带宽约束。

- 使用 ** 交替方向乘子法（ADMM）** 迭代更新每个 IMF m_k 和中心频率 ω_k，通过 Wiener 滤波优化频域分解，确保抗噪声和采样鲁棒性。

(5) 中心频率更新

- 每个 IMF 的中心频率 ω_k 由其功率谱的重心确定：

$$\omega_k^{n+1} = \frac{\int_0^\infty \omega \left| \hat{m}_k^{n+1}(\omega) \right|^2 d\omega}{\int_0^\infty \left| \hat{m}_k^{n+1}(\omega) \right|^2 d\omega}$$

确保 IMF 紧密围绕其主导频率。