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3DVidar: A Single mmWave Radar based 3D Vibration Sensing Method via Multi-Point Multi-Path Multi-Antenna Enhancement

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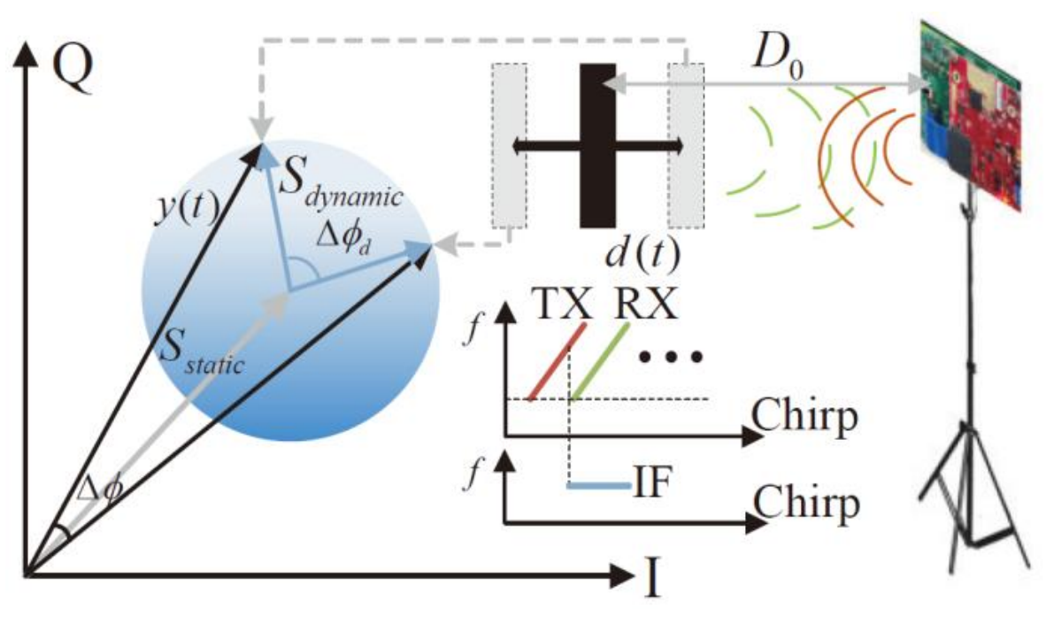
BACKGROUND

- **Industry 5.0**
  - Higher requirements are placed on the efficiency and reliability of industrial systems.
  - Industrial equipment running for long periods is prone to failure.
- **Vibration Sensing**
  - Abnormal vibrations in machinery can often be an early sign of potential safety incidents.
  - Vibration sensing allows for real-time tracking of equipment status.
- **Existing Vibration Sensing Technologies**
  - Contact-based Method: Attaching vibration sensors directly.→ Potential Deployment Issues.
  - Contact-free Solutions: Laser systems and high-speed cameras.→ High Cost.
- **Wireless Vibration Sensing Solutions**
  - RFID and UWB radar: Low-frequency vibrations with relatively large amplitudes.
  - **mmWave Radar**: High-frequency, weak vibrations of industrial equipments.

MMWAVE BASED VIBRATION SENSING

Technical Principles

Current mmWave radar-based vibration sensing methods primarily focus on 1D radial vibration or 2D vibration trajectories.



Basic vibration sensing model.

$$s_{TX}(t) = \exp\left[j(2\pi f_c t + \pi K t^2)\right],$$

$$s_{RX}(t) = \alpha s_{TX}\left[t - \frac{2D(t)}{c}\right],$$

$$s_{IF}(t) = s_{TX}(t)\cdot s^*_{RX}(t) \approx \alpha \exp\left[j2\pi\left(\frac{2f_c D(t)}{c} + \frac{2KD(t)}{c}\cdot t\right)\right].$$

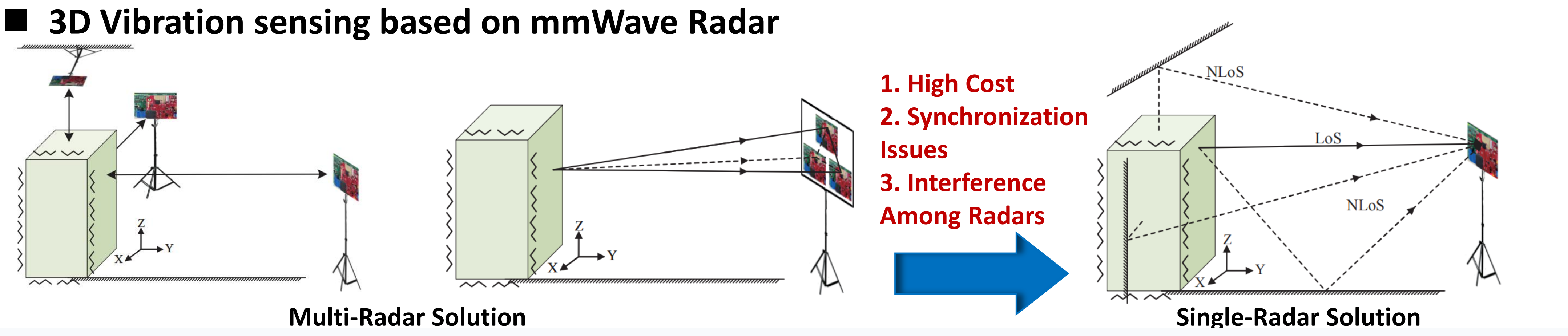
The transmitted and received signal.

$$\phi(t) = \frac{4\pi f_c D(t)}{c} = 4\pi f_c\frac{D_0}{c} + 4\pi f_c\frac{d(t)}{c} \overset{\text{def}}{=} \phi_0 + \Delta\phi(t),$$

$$\boxed{d(t) = \frac{c}{4\pi f_c}\left(\Delta\phi(t)\right),}$$

Relationship between phase change and vibration

3D Vibration sensing based on mmWave Radar



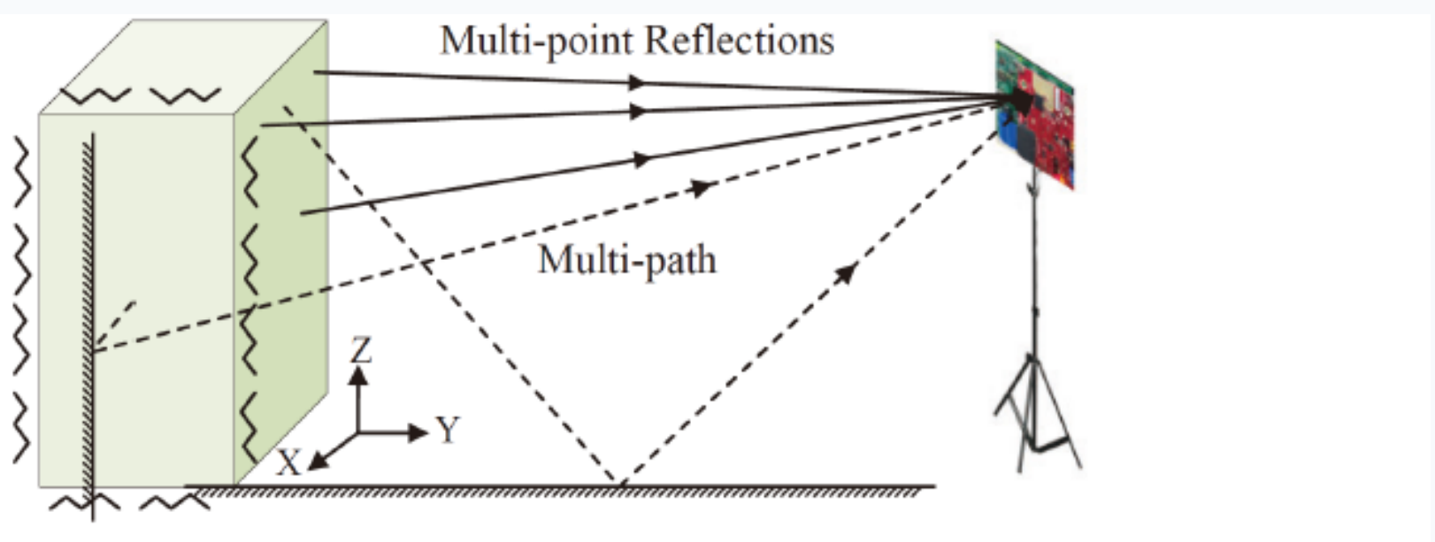
1. High Cost
2. Synchronization Issues
3. Interference Among Radars

Multi-Radar Solution **Single-Radar Solution**

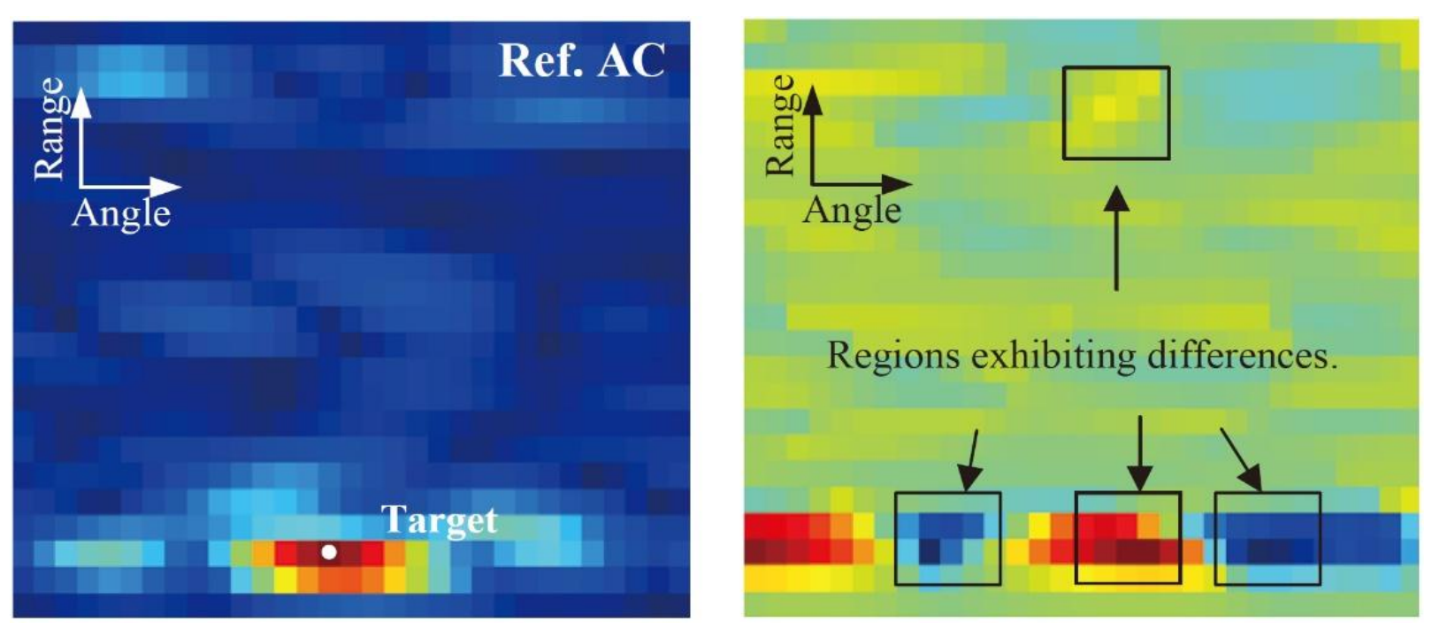
- Objective: Use a single radar to recover the 3D vibration trajectory of the target.
- Challenge1: Radar lacks tangential sensitivity, limiting 3D vibration recovery.
- Challenge2: Radar echoes complicate 3D vibration mapping due to complex superpositions.

MOTIVATIONS AND SOLUTIONS

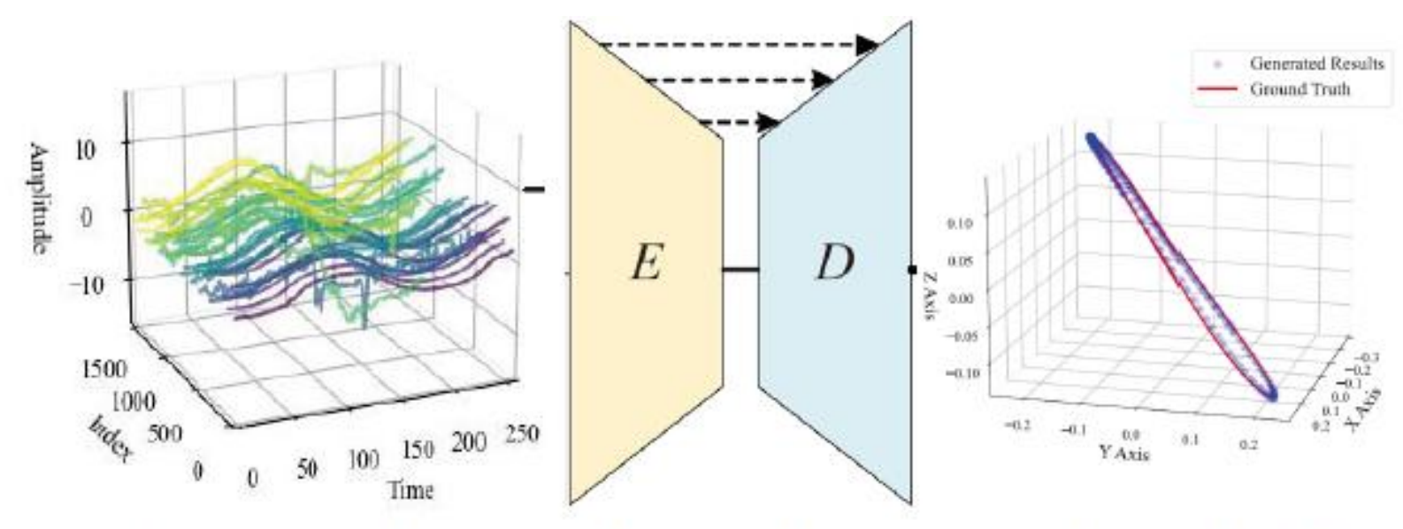
- **Motivations**
  - Multipath signals can help enrich vibration information.
  - Multiple antennas combinations can offer multi-view of the target vibration.
  - AI based approaches have strong capacity to learn complex mapping relationship.



Target Multipath and Multi-Point Signal Reflections.



DERAM reveals variations in signal amplitude

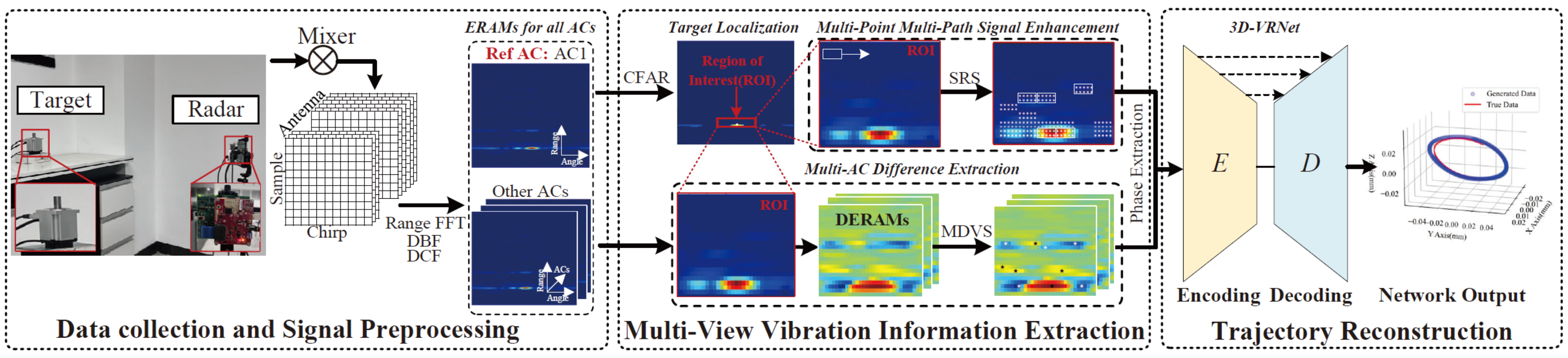


AI based approaches to learn the mapping relationship

- **Solutions**
  - Utilize multiple paths-points-antennas to expand information dimensions.
  - Use AI based approaches to learn the 3D vibration mapping relationship.

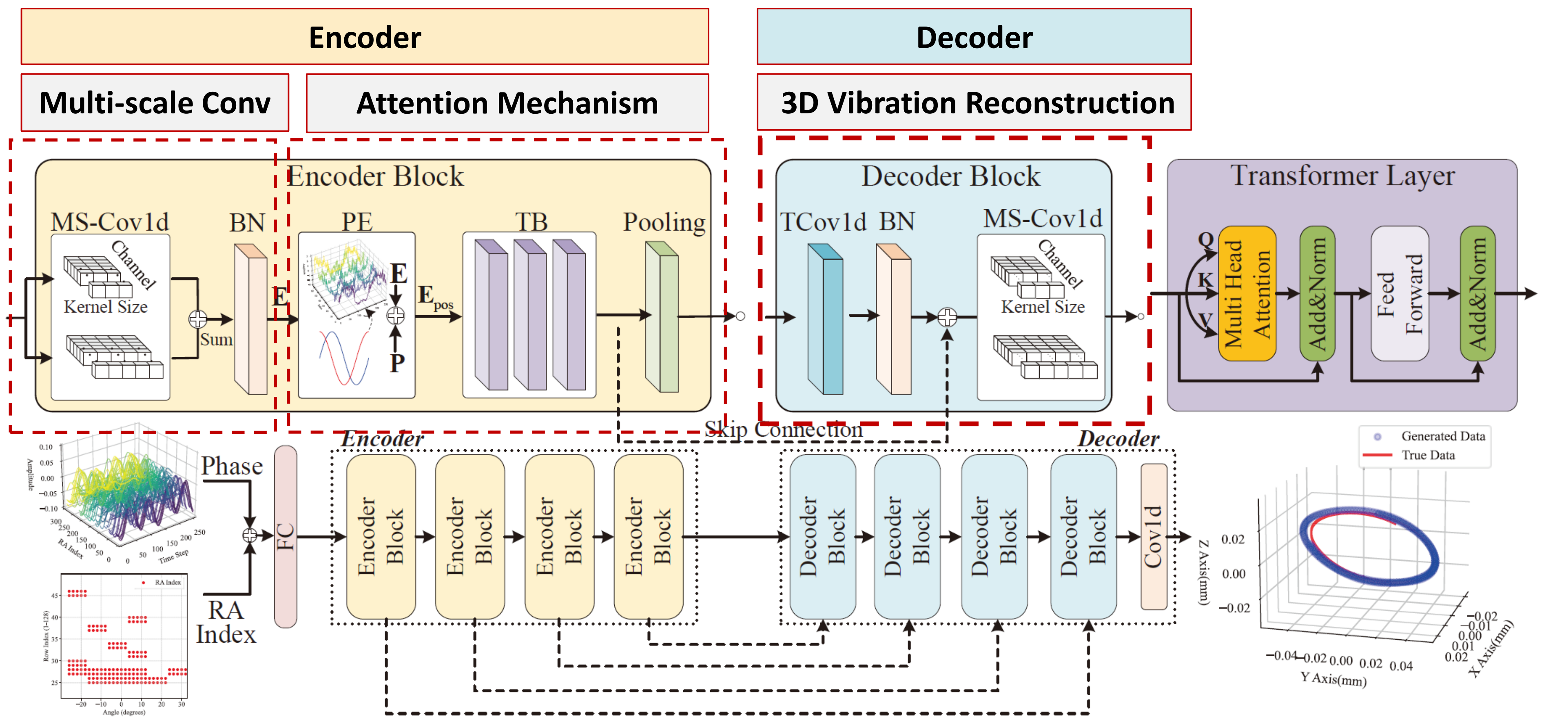
SYSTEM DESIGN

Solution



Data-Driven Approach

An Encoder-Decoder architecture is employed to extract features and reconstruct the 3D vibration trajectory.



Input : Multi-view Radar Phase Data **Network Architecture: TriVFormer** **Output : 3D Vibration Trajectory**

EXPERIMENT

Performance Comparison

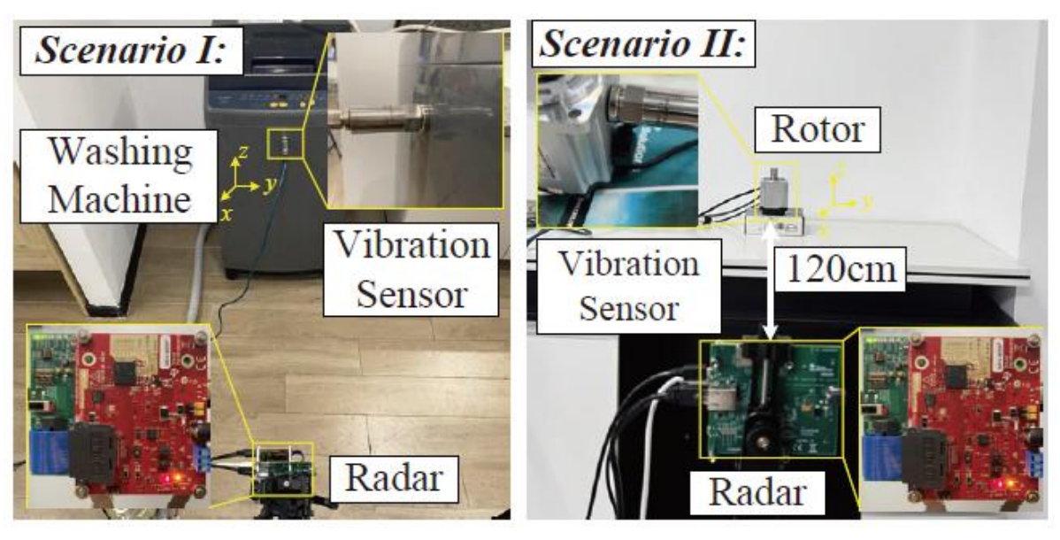


TABLE III
ABLATION STUDY. ↓: THE LOWER THE BETTER.

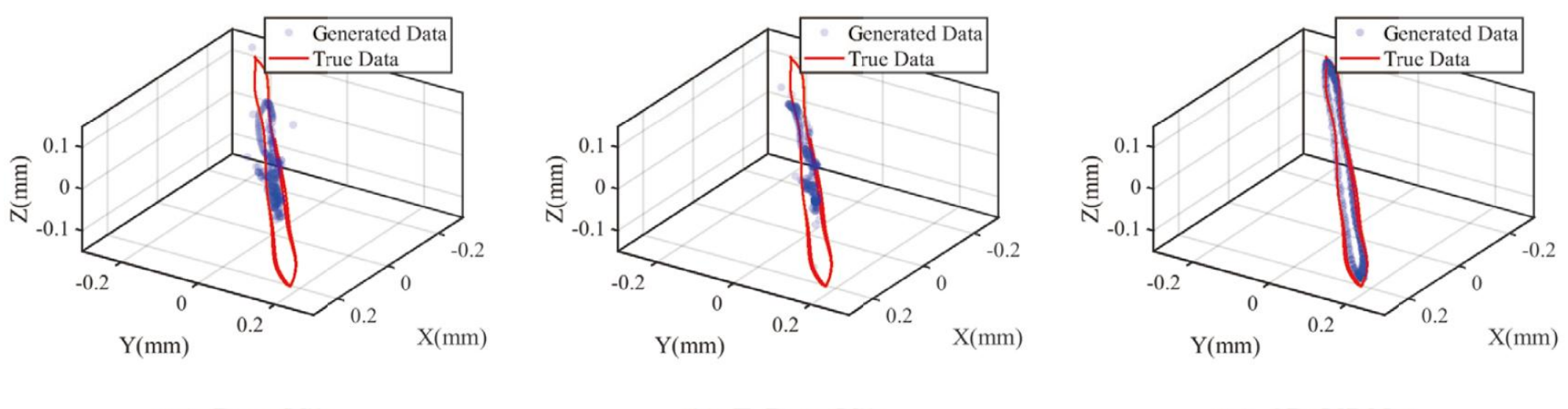
Formulation	AAFE(Hz)↓	AAPPE(mm)↓
3DVidar (w/o TB)	5.3517	0.1171
3DVidar (w/o MP^{2}SE&MADE)	1.2985	0.1421
3DVidar (w/o Emb)	0.6931	0.0425
3DVidar (w/o MADE)	0.5306	0.0387
3DVidar (**Ours**)	**0.4811**	**0.0303**

Network ablation studies demonstrate the effectiveness of the self-attention mechanism, while architectural ablation experiments validate the contribution of multi-point and multipath signals.

TABLE IV
QUANTITATIVE COMPARISON OF AAFE AND AAPPE ERRORS UNDER DIFFERENT SCENARIOS AT VARYING CDF PERCENTILES. THE BEST RESULTS ARE HIGHLIGHTED IN **BOLD**. ↓: THE LOWER THE BETTER.

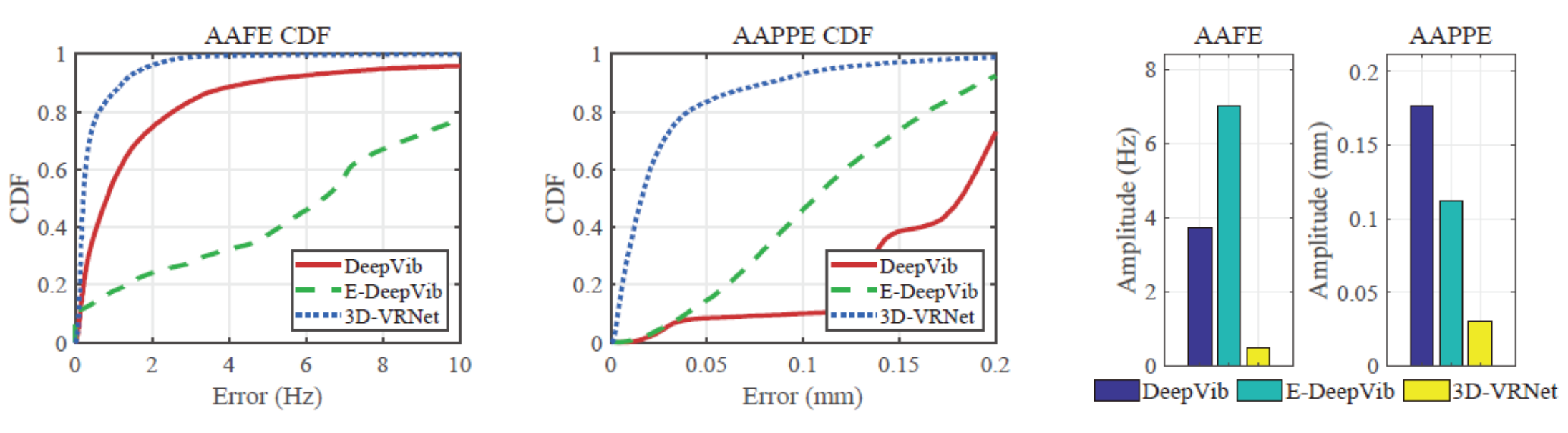
Scenario	Metric	Method	Mean	CDF Percentiles 50%	80%	90%	95%
Scenario I	AAFE (Hz)↓	Trad-Factorization [41]	4.3886	3.0239	9.2467	12.2109	13.9364
		TriVFormer [1]	0.6931	0.2611	0.8337	1.5560	2.4837
		3D-VRNet	**0.4811**	**0.2029**	**0.6129**	**1.2235**	**1.7674**
	AAPPE (mm)↓	Trad-Factorization [41]	0.3363	0.3450	0.4685	0.4956	0.5166
		TriVFormer [1]	0.0425	0.0242	0.0747	0.1066	0.1391
		3D-VRNet	**0.0303**	**0.0161**	**0.0401**	**0.0812**	**0.1144**
Scenario II	AAFE (Hz)↓	Trad-Factorization [41]	3.8703	0.8871	6.4389	15.2057	17.5289
		TriVFormer [1]	2.0884	0.6765	3.2950	6.4437	9.0714
		3D-VRNet	**1.9771**	**0.6662**	**3.2132**	**6.0379**	**8.1600**
	AAPPE (mm)↓	Trad-Factorization [41]	0.2102	0.2038	0.2628	0.3010	0.3441
		TriVFormer [1]	0.0155	0.0121	0.0259	0.0325	0.0384
		3D-VRNet	**0.0149**	**0.0115**	**0.0252**	**0.0303**	**0.0364**

Performance under different learning-based methods.



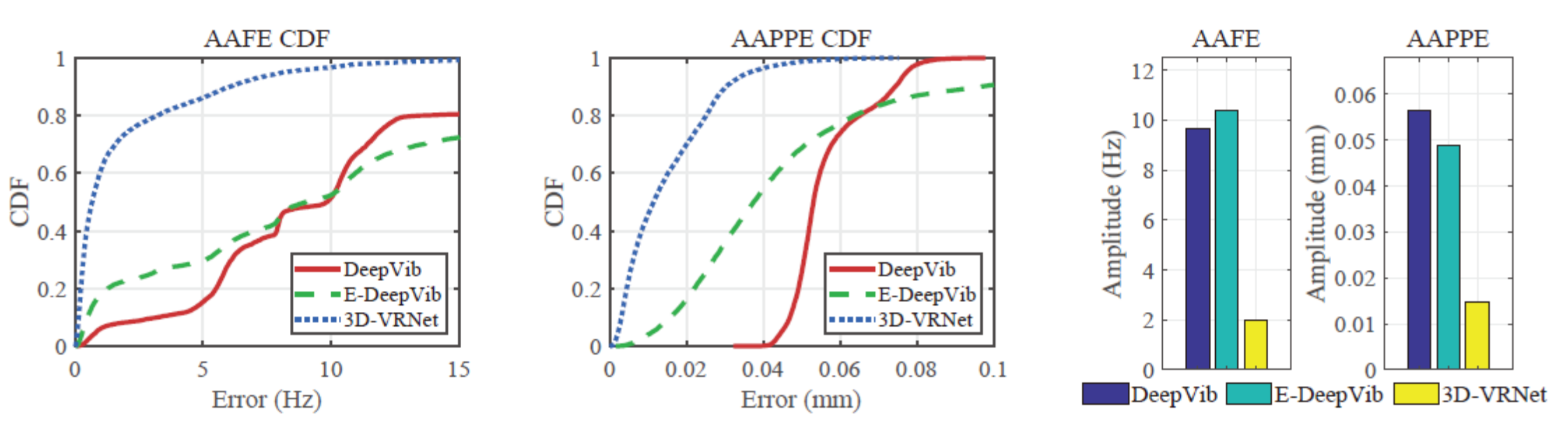
(a) DeepVib. (b) E-DeepVib. (c) 3D-VRNet.

Scenario I



(a) AAFE CDF. (b) AAPPE CDF. (c) Overall mean error.

Scenario II



(a) AAFE CDF. (b) AAPPE CDF. (c) Overall mean error.

CONCLUSION

- In this paper, we propose 3DVidar, a contact-free 3D vibration sensing system using a single mmWave radar. We develop multi-point multi-path signal enhancement and virtual antenna combination methods to fully expand the radar information from different views.
- Then, we propose a 3D vibration reconstruction network (3D-VRNet) to learn the complex relationship between the radar information and the 3D vibration trajectory. We implement 3DVidar on a commercial mmWave radar. The results demonstrate that it can effectively reconstruct 3D vibration trajectories of different targets under various conditions, achieving low mean errors in both frequency and amplitude.
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