Navigation and Viewpoint Optimization for mmWave Radar-Based Contactless Vital Sign Extraction

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Background

- Continuous, contactless vital sign monitoring is essential for healthcare applications (ICU, elderly care).
- Wearable sensors require skin contact and are not always practical.
- Camera-based methods raise privacy concerns and depend on lighting.
- mmWave radar enables privacy-preserving sensing with sub-millimeter motion detection.
- Fixed radar placement causes occlusion and degraded signal quality at non-optimal viewing angles.

Motivation and Contribution

- mmWave sensing is highly viewpoint-dependent; performance drops at oblique angles.
- Fixed sensors cannot adapt to posture or environment changes.
- We propose an autonomous robotic system to optimize sensing viewpoint.
- Our system integrates pose estimation, viewpoint optimization, navigation, and signal processing.
- Achieves 2.6× improvement in heart rate accuracy (4.62 BPM vs 12.00 BPM).

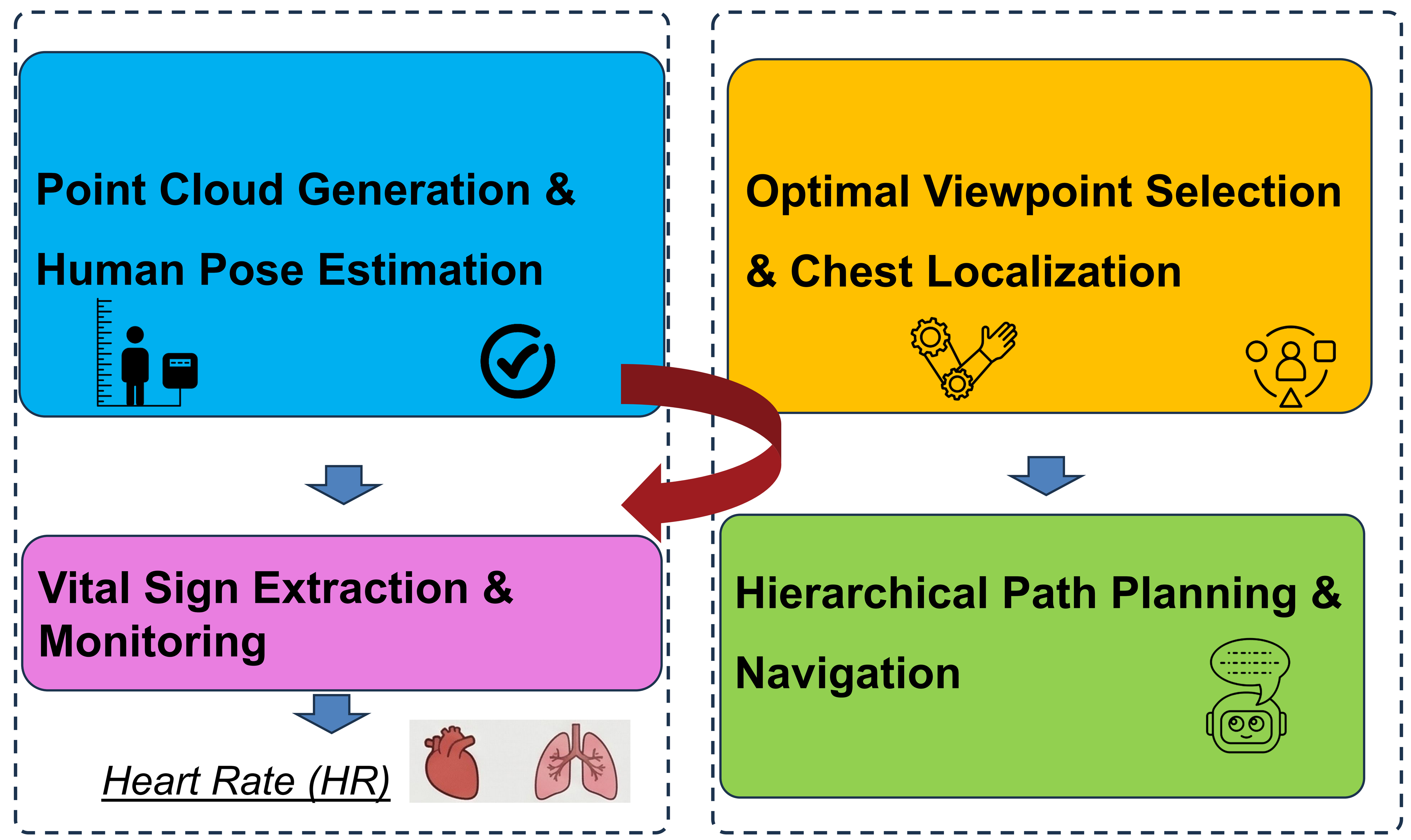
Challenges

- Sparse and noisy radar point clouds make pose estimation difficult.
- Optimal viewpoint requires joint consideration of angle, distance, and occlusion.
- Perception, planning, and sensing are tightly coupled.
- Robot motion introduces vibration and phase noise.
- Real-world environments are dynamic and introduce sim-to-real gaps.

[1] K. Harlow, “A new wave in robotics: Survey on recent mmwave radar applications in robotics,” arXiv , 2024.

[2] H. Xue, “MM-mesh: Towards 3d realtime dynamic human mesh construction using millimeterwave.” ACM, 2021, pp. 269-282.

System Overview

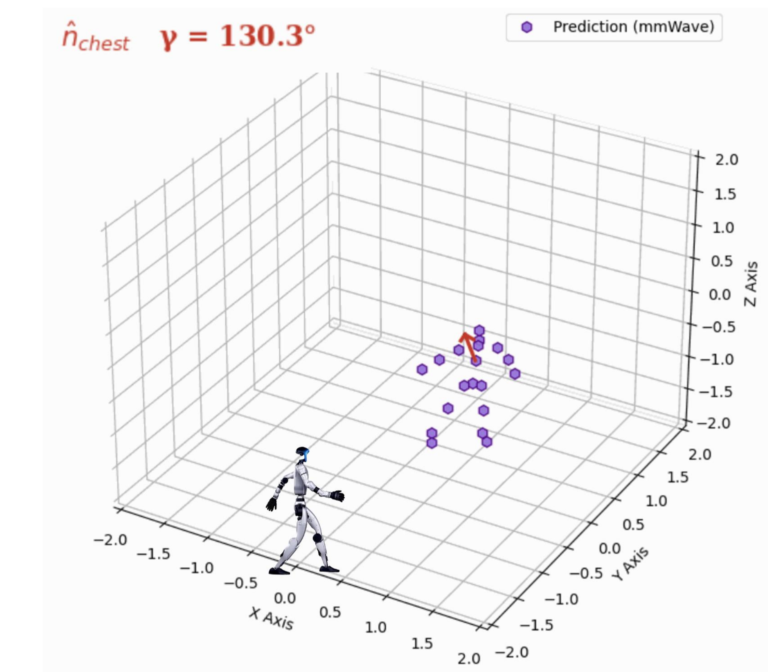


Methodology

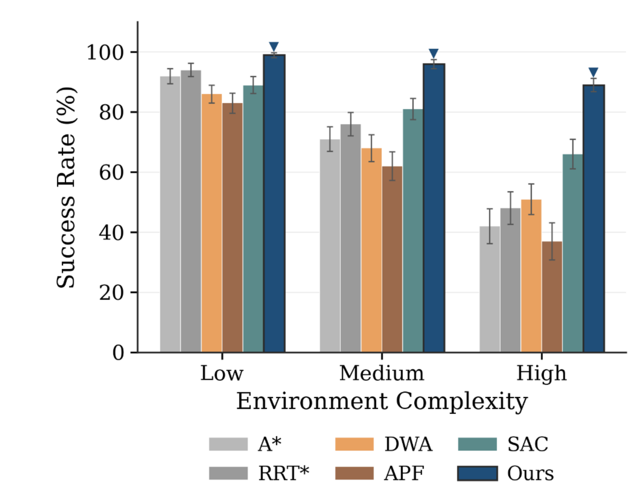
- **Radar Signal Processing:** Three sequential FFT operations (Range-FFT, Doppler-FFT, Angle-FFT) extract 3D point clouds with range, velocity, azimuth, and elevation from raw chirp signals, followed by static-clutter removal and dynamic peak selection.
- **Radar-Based 3D Pose Estimation:** mmMesh and MARS networks regress anatomical keypoints from sparse point clouds. The chest surface-normal vector is computed from left shoulder, right shoulder, and mid-spine joints to determine body orientation.
- **Cost-Function-Based Viewpoint Selection:** A cost function jointly optimizes three criteria derived from sensing physics: radial alignment, optimal distance (0.3–0.7 m), and elevated occlusion avoidance.
- **Hierarchical Hybrid Path Planning:** A four-layer framework combines DBSCAN perception, Improved A*/PB-RRT global planning with EKF belief-space optimization, Score-Weighted APF and GAP_SAC DRL for local avoidance, and hybrid integration with dynamic replanning.
- **Vital Sign Extraction:** Target isolation, second-derivative respiratory suppression, Harmonic Product Spectrum, and BeamDA extract heart rate while the robot remains stationary.

Results

- **Viewpoint Validation (Front vs Side)::**
  - ✓ At $\gamma \approx 0°$ (front-facing): MAE 4.62 BPM, MedAE 1.03 BPM, 80% within ±5 BPM.
  - ✓ At $\gamma \approx 90°$ (side-facing): MAE degrades to 12.00 BPM (~2.6× worse), only 23% within ±5 BPM.Each
  - ✓ Signal validity drops from 33.6% to 21.7% at oblique angles.
  - ✓ Spatial sweep validates all three viewpoint criteria (angle, distance, elevation).



- **Path-Planning Benchmark (MuJoCo digital twin):**
  - ✓ Proposed planner maintains ~95% success rate at Low/Medium and 90% at High complexity.
  - ✓ Achieves 24% reduction in navigation time vs best baseline (SAC) in high clutter.
  - ✓ Highest signal-quality integral (0.88/0.82/0.74), substantially outperforming A*, RRT*, DWA, APF, and SAC.



(a) Navigation Success Rate.

- **Vital Sign Extraction:**
  - ✓ MAE 4.51 BPM, RMSE 7.81 BPM (n = 20).
  - ✓ Bland–Altman bias +2.84 BPM, 85% within 95% LoA.