Review: mmWave Radar Point Cloud Processing Technology for Human Activity and Posture Recognition

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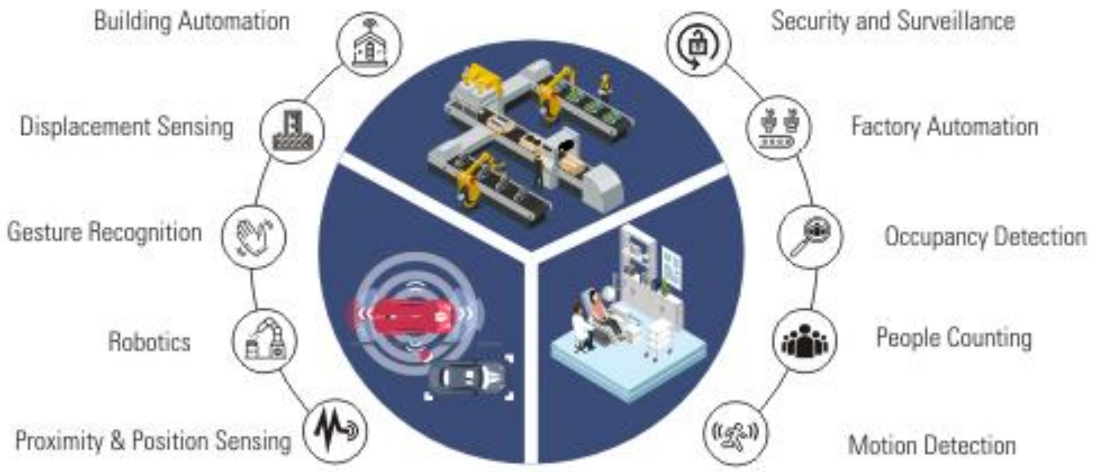
Agenda

- Radar Technology
- Point Clouds
- Use Cases
  - HTAR using micro-Doppler Characteristics
  - Voxelized Points Cloud
  - Multi-Dimensional Point Clouds
  - Point Clouds and Range-Doppler

Introduction



- **Research Trend:** mmWave Radar are gaining popularity due to their ability to operate in challenging environments while ensuring privacy in comparison to traditional camera monitoring face privacy concerns and limitations in low light conditions.
- **Applications:** Healthcare, military, public safety, autonomous driving, offering real-time localization, activity recognition and pose estimation

https://www.youtube.com/watch?v=XJ6JhB8wOPU

Background

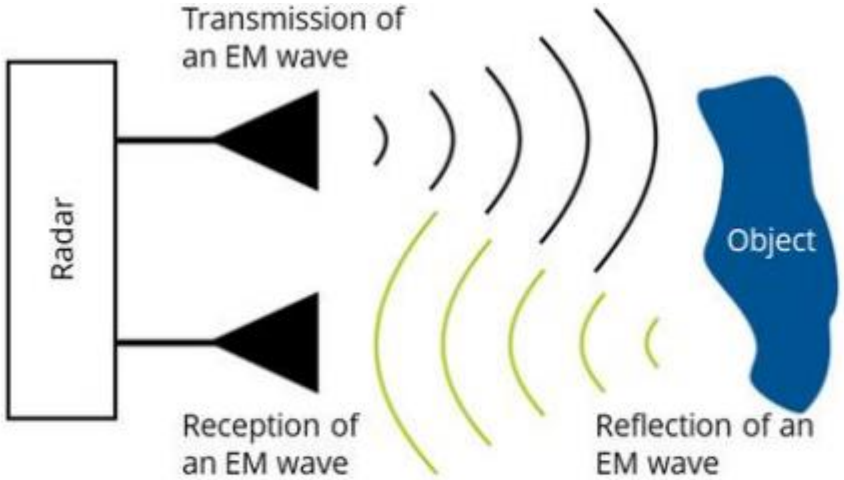


Figure (1): Radar basic working principle: The object is detected by comparing the transmitted (TX) and the received (RX) electromagnetic wave.[96]

Main Components

- **Key parameters:** Speed the rate of movement of detected object, Distance between radar and the object, Azimuth the angle or direction of the object relative to the radar. Where accuracy is determined by time delay and Doppler frequency estimates
- **Radar Types:** classifications are
  - **Wavelength:** measures in meter or decimeter range with low range and strong penetration used for broadcasting, military early warnings and satellite communications are called long-wave radar while in cm or mm range with high resolution and poor penetration used in surveying, short-range communication and vehicle applications are short-wave radar
  - **Waveform:** determines target distance based on the time difference between pulse transmission and reception its principle is similar to LiDAR called Pulse Radar while transmits a continuous signals, where the frequency changes with time (frequency modulation) allows for speed measurements and is often referred to as FMCW (frequency modulated continuous wave)

FMCW

- **Operation:**
  - Transmits sequences of a linear frequency modulated signal called chirp signal
  - Such signals increases linearly with time over a bandwidth range that reach upto 4GHz and a carrier frequency range of 76-81GHz.
  - Core principle involves transmission of an electromagnetic signal that is then reflected by objects in its trajectory
  - Once the moving object with respect to the radar been detected the Doppler effect take place at receiving end, these received signals are mixed with the transmitted chirp signals in a mixer

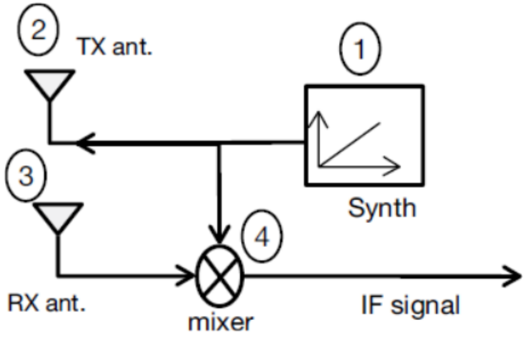


Figure (2): Block diagram of a FMCW radar. The synthesizer is responsible for the chirp generation, the mixer mixes received (RX) and transmitted (TX) obtaining in output the intermediate frequency (IF) signal, which is analyzed to find target(s).[51]

Figure (4): Radio wave signal which changes frequency due to Doppler effect caused by the movements of the detect moving objects.[97]

FMCW

- **Operation:**
  - Finally, the operational mechanism of FMCW radars, delta t which represents the time difference between the transmitted and received signals, delta f the discrepancy in frequency, fD the frequency shift instigated by the Doppler effect
  - If multiple targets are detected, the IF signal will consist of several sinusoids, each having a unique frequency corresponding to a specific target

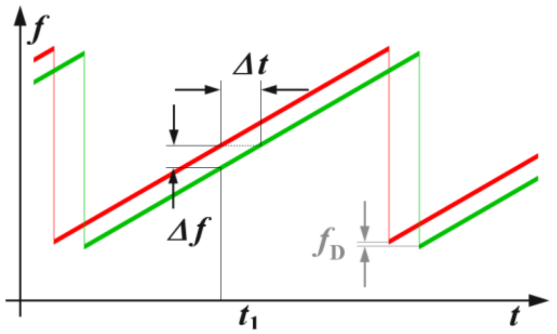


Figure (5): Operational mechanism of FMCW radars to Doppler effect.

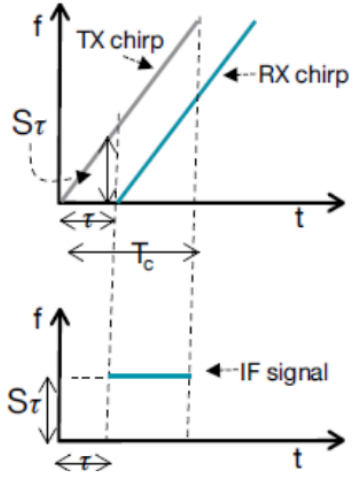


Figure (6): Intermediate frequency (IF) resulting from the mixer output, a signal with constant frequency.[51]

Radar Signal

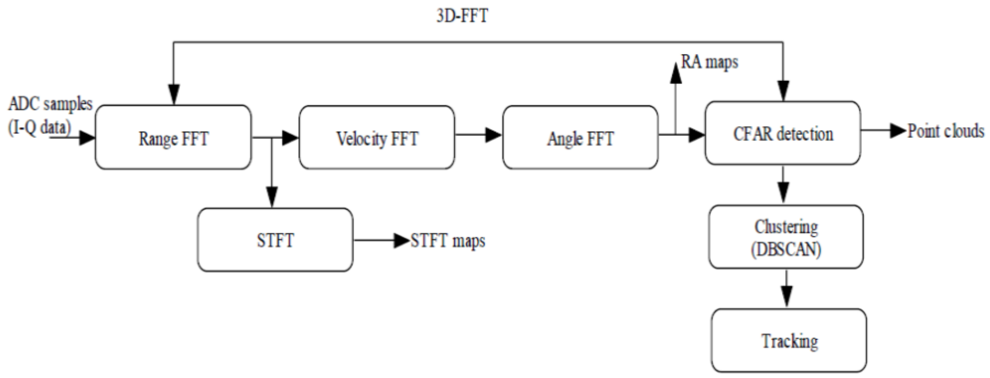


Figure (10). Radar signal processing and imaging. Adapted from [60]

Processing: it has seven distinct stages which transform raw radar data into meaningful information about targets

- Formation of 3D Radar Cube: Radar signals (ADC) are received as input data (CPI) where the raw data is structured into matrix frames, creating 3D radar cube with axis, rapid time by chirp index, slow time by chirp sampling and phase represented by Tx/Rx antenna pairs
- Range and velocity determination using 2D-FFT: is applied to the 3D radar cube to compute the range where first FFT is applied to determine the distance to the targets and second FFT is applied to determine the speed of the target relative to the radar. Where the result of two FFTs is a 2D map. To differentiate the real targets and noise third FFT is applied to the strongest Doppler peaks to provide angle estimation. After 3D-FFT (range, velocity and azimuth) a map (spectrogram) is created by using short time FT to provide a visual representation of the target's velocity
- Target detection algorithm: Constant false alarm rate (CFAR) is used for each calculating thresholds (adjusting based on noise variance) in different ways, to improve target detection. After 3D point clouds are generated by applying the angle FFT to the range velocity bins CFAR detection outputs
- Clustering of Detected Target: Density based spatial clustering of applications with noise (DBSCAN) algorithm is used to differentiate between multiple targets
- Target tracking: Kalman filter is used to estimate (accurate tracking and prediction of the target's future position) the position and trajectory of each target

Data Representation

mmWave Radar Processing to Collect Data: In mmWave radar processing, point clouds are a critical representation of the data collected by the radar system, particularly in applications such as human tracking, activity recognition, gesture recognition, autonomous driving, and object detection. Point clouds are used to provide a spatial and dimensional representation of objects or people within the radar's detection range. The use of point clouds offers several advantages in processing and analyzing radar data.

- <u>Human tracking and gesture recognition</u>: point clouds can represent different poses or actions. By analyzing these point clouds, the radar system can identify specific activities like walking, running, sitting, or even complex gestures, such as arm movements.
- <u>Pose estimation and human body analysis</u>: 3D point clouds represent the locations of various body parts, allowing for accurate modeling of the person’s pose. These point clouds can be processed to extract joint positions e.g. elbows, knees, shoulders. Further, in healthcare applications or assistive technology for elderly care, mmWave Radar point clouds can be used to monitor body movements and detect falls, abnormal activity or health conditions

https://www.youtube.com/watch?v=yXCkyuo8bcs

Purpose?

- **Converting Range-Doppler Map to Point Cloud Data:** The range-Doppler map is the initial format in which the millimeter-wave radar (mmWave radar) presents the collected signal. This map is a two-dimensional representation where the range (distance of the target) is plotted on one axis, and the Doppler shift (velocity of the target) is plotted on the other. However, to make the radar data more **meaningful for applications** like object detection, tracking, and human activity recognition, this 2D range-Doppler map needs to be converted into point cloud data.
- **Benefits of Point Cloud Representation**: 3D spatial understanding (scene reconstruction, object recognition), Detailed target analysis (shape, size, speed and trajectory), Data clustering and tracking (using clustering algorithms to separate targets from noise and to track their movement over time)

Converting Range-Doppler Map to Point Cloud Data

- **Process Flow:** From previous figure of processing radar signal, the process of generating a 3D point cloud is used by applying an angle FFT to the CFAR detection of the range-velocity bins as follows:
  1. Radar signal is received and processed to create a range-velocity map
  2. Apply CFAR detection to the graph to determine the threshold level for detecting objects in the presence of noise. If the signal in a bin exceeds this threshold, it is considered detected
  3. Then, apply an angle FFT to these signals. This FFT is preformed along the angular dimension of the range-velocity plot, transforming the detected signal into the frequency domain
  4. The result of this angular FFT can be used to generate a 3D point cloud. Each point in the cloud corresponds to a detected target, and the coordinates of the point represent the distance, velocity and angle of the target

  This method is the most common existing method for translating between range-Doppler signals and point cloud data, which helps to generate a spatial representation of detected objects in the form of 3D point clouds.

Characteristics

The rapid progress of ***low-cost sensors*** such as time-of-flight cameras, millimeter-wave radar, LiDAR and Kinect, has made the acquisition of point cloud data change. The simplicity also enables the rapid advancement of point cloud processing techniques based on these sensor collections. In general, the processing of the obtained human body point cloud data includes the following stages

- **Filtering** to remove outliers and reduce noise e.g. voxel grid filtering
- **Segmentation** typically represents various object or its parts e.g. Euclidean clustering
- **Feature extraction** it involves the extraction of certain features from each segment like height, width, depth etc.
- **Classification** extracted features are then fed into a classification algorithm (CA) to determine either segment is representative of a human, CA are Random Forest, Recurrent Neural Network etc.
- **Tracking** if the classification step determines that a human has been detected the system can track the movement of the person through continuous radar scans e.g. Kuhn-Munkres Algorithm
- **Recognition** at this stage specific activity or behavior performed by a person is identified based on the detected movements patterns various ML and DL models can be employed to accomplish this task which involves HAR like walking or standing to more complex behavior like running, jumping etc.
- **Reconstruction** finally to reconstruct human pose from point cloud data in-order to identify and locate key points of the skeleton and reconstruct the pose of the human body

mmWave Radar Application

latest advances in mmWave radar-based Human Activity Recognition (HAR), particularly focusing on the recognition of human activities such as gait detection for elderly fall detection

- **Human Activity Monitoring** there is an increasing demand for human activity monitoring, especially in public places and indoor environments
- **Limitations in Traditional Sensors** like Cameras (are only effective in controlled environments but are prone to visual occlusion, in particular when obstacles or blind spots are present), LiDAR (it suffers high costs and is also subject to limitations such as low resolution in fog, rain smoke), Harsh environmental conditions (strong lighting or reflective surfaces)
- **Benefits** privacy friendly (requires no visual data), immunity to harsh conditions (highly resilient to environmental disturbances), low cost and small size (with high performance offerings)

Micro-Doppler Characteristics

The author collects **two kinds of millimeter-wave radar** and named it as micro-Doppler data.

1. The first is the raw Doppler data collected by the radar <u>without integrated</u> CFAR algorithm.
2. The other is converted from the 3D point cloud information collected from the radar system <u>integrated with</u> the CFAR algorithm

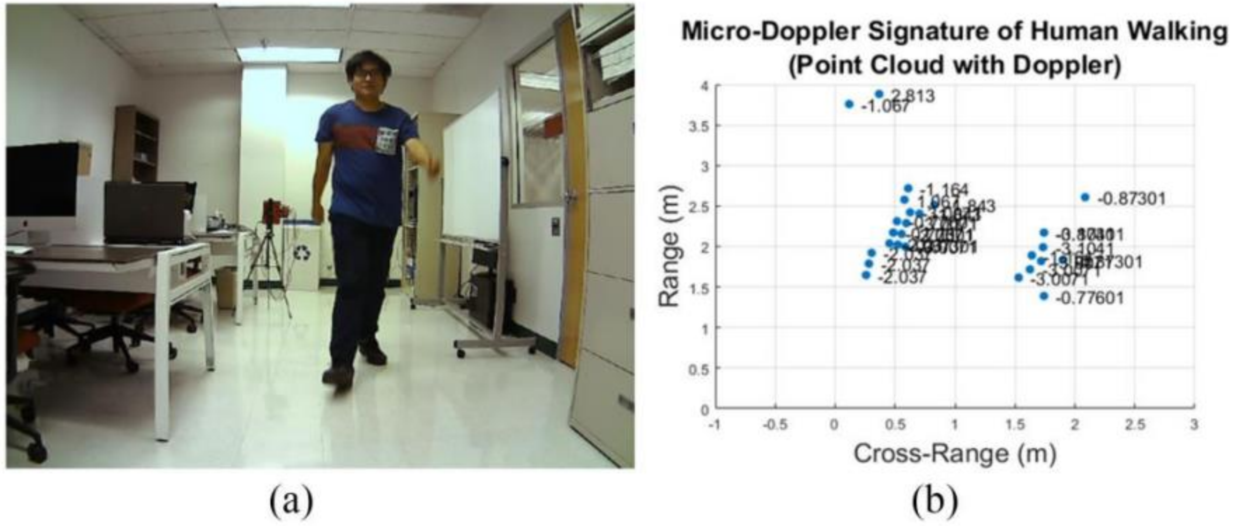


Figure (14). Real-time micro-Doppler prediction scene. (a) Camera vision. (b) Radar point cloud output with Doppler velocities in meter per second [1]

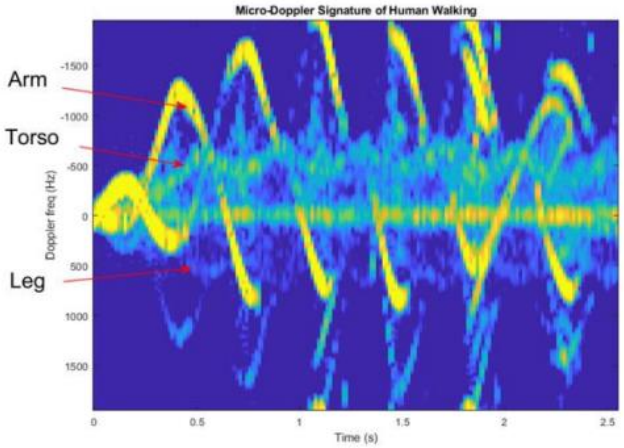


Figure (15). Micro-Doppler signature of a human walking.

R. Zhang and S. Cao, "Real-Time Human Motion Behavior Detection via CNN Using mmWave Radar," in IEEE Sensors Letters, vol. 3, no. 2, pp. 1-4, Feb. 2019, Art no. 3500104, doi: 10.1109/LSENS.2018.2889060

Voxelized Points Cloud

A **voxelized point cloud** refers to a process where 3D point cloud data is transformed into a grid of **voxels**, which are 3D volumetric elements, similar to how pixels represent 2D image elements. This transformation simplifies the processing and analysis of point clouds by discretizing the 3D space into uniform, small cubic cells, or "voxels."

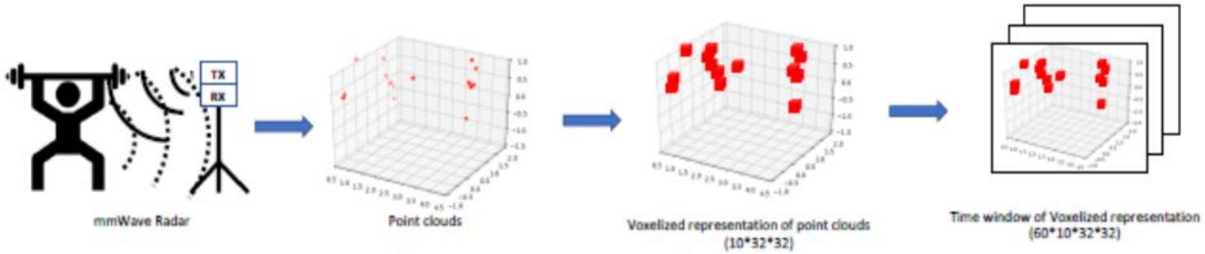


Figure (18): Workflow of data preprocessing. The voxel size if 10*32*32. The time windows are generated by grouping 60 frames (2 second) together.[3]

Figure (17): Data collection setup.[3]

Akash Deep Singh, Sandeep Singh Sandha, Luis Garcia, and Mani Srivastava. 2019. "RadHAR: Human Activity Recognition from Point Clouds Generated through a Millimeter-wave Radar." In Proceedings of the 3rd ACM Workshop on Millimeter-wave Networks and Sensing Systems (mmNets'19). Association for Computing Machinery, New York, NY, USA, 51–56. https://doi.org/10.1145/3349624.3356768

Multi-Dimensional Points Cloud

The method of **multidimensional data** to obtain more information elements in order to directly or indirectly improve the accuracy of the model, but the improvement of the data dimension is bound to be accompanied by model design. <u>The increase in complexity, the increase in training time, the increase in cost and the extension of recognition time</u>.

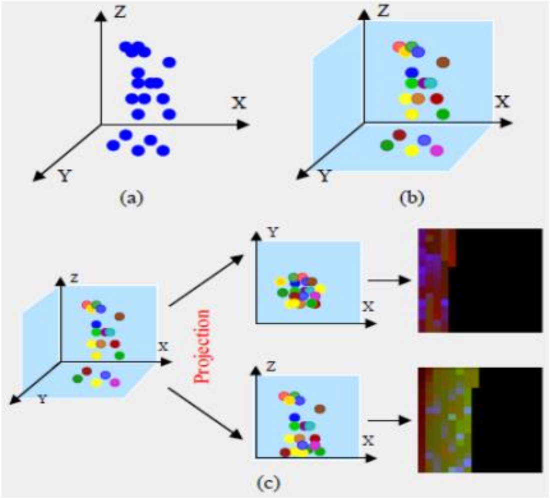


Figure. (26). (a) Point-cloud of the target in 3-D space; (b) Point-cloud of the target with the reflected power use RGB weight represent; (c)Projecting the point-cloud in the XY and XZ planes,[4]

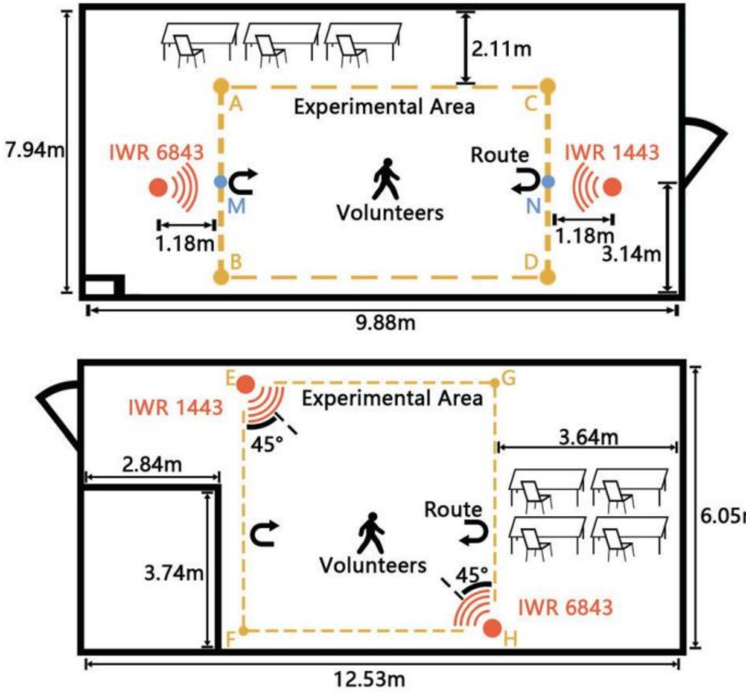


Figure (28): Experimental scenario 1 simulates walking in the corridor facing the equipment. At this time, the effective horizontal detection angle of the equipment is ±60°. Scene2 simulates walking in the living room. At this time, the effective horizontal detection angle of the equipment is ±45°. [5]

Arindam Sengupta, Feng Jin, Renyuan Zhang, Siyang Cao: "mm-Pose: Real-Time Human Skeletal Posture Estimation using mmWave Radars and CNNs." arXiv:1911.09592

Meng, Z., Fu, S., Yan, J., Liang, H., Zhou, A., Zhu, S., Ma, H., Liu, J., & Yang, N. (2020). "Gait Recognition for Co-Existing Multiple People Using Millimeter Wave Sensing." Proceedings of the AAAI Conference on Artificial Intelligence, 34(01), 849-856. https://doi.org/10.1609/aaai.v34i01.5430

Points Clouds and Range-Doppler

We have already introduced the method of directly using **micro-Doppler features**, the method of **voxelizing 3D point cloud**, and the method of using **multi-dimensional point cloud data**. All of these have one thing in common, which is to use single-form data for analysis. So, is it possible to use micro-Doppler features and 3D point cloud data for analysis at the same time?

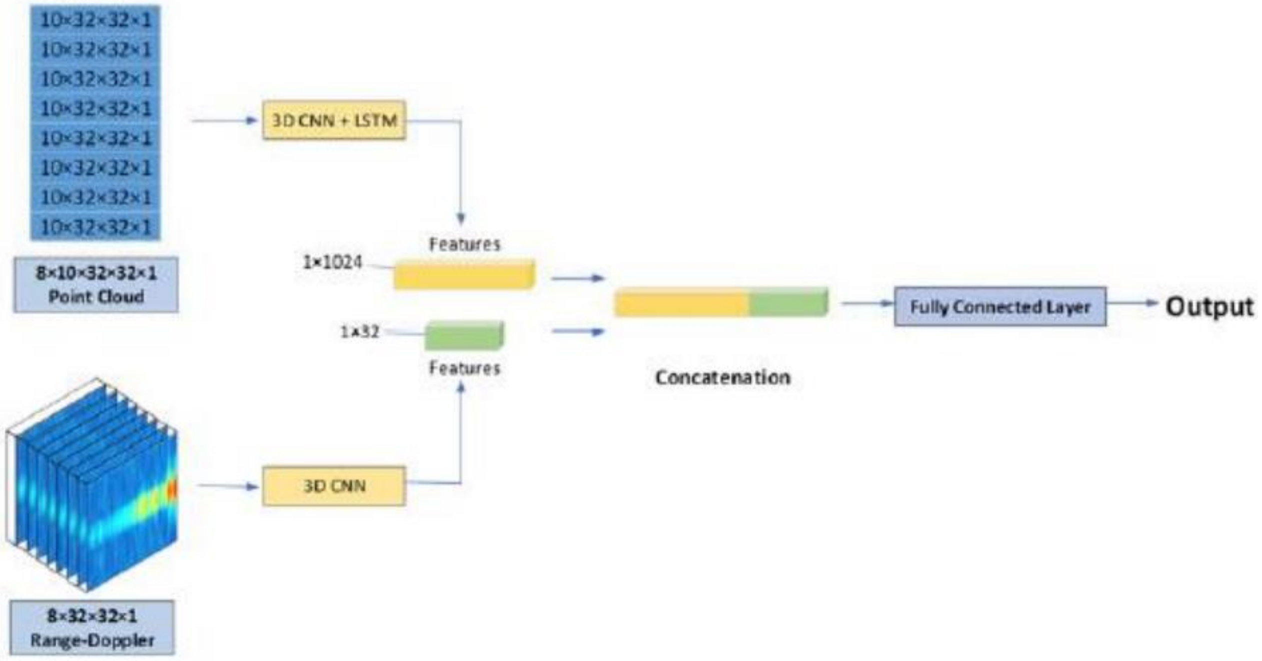


Figure (41). The structure of the fusion network.[15]

Huang, Y.; Li, W.; Dou, Z.; Zou, W.; Zhang, A.; Li, Z. “Activity Recognition Based on Millimeter-Wave Radar by Fusing Point Cloud and Range–Doppler Information.” Signals 2022, 3, 266-283. https://doi.org/10.3390/signals3020017

Experimental Details

https://www.ti.com/product/es-mx/IWR1443BOOST/part-details/IWR1443BOOST

https://www.youtube.com/watch?v=hzAm15KZOSk

https://www.youtube.com/watch?v=srLBuHDuiEs

Table XI. Comparison of Methods for Human Activity Recognition

Reference	Senser	Data Type	Deep Learning Model
[1]	IWR1642 [100]	Micro-Doppler signatures	CNN
[3]	IWR1443-BOOST [66]	3D voxel	Time-distributed CNN+ Bi-directional LSTM
[5]	2*IWR6843[101] 2*IWR1443[66]	5D point cloud	5 channels-Attribute Networks
[6]	4*TI AWR1243 [102]	2D point cloud	2D CNN
[7]	IWR1443Boost [66]	5D point cloud	5D Radar point cloud
[9]	4*AWR1243 FMCW [102]	3D point cloud	CNN + LSTM
[15]	IWR1843 [84]	3D point cloud + range-Doppler data	3D CNN+LSTM & 3D CNN Parallelized
[16]	IWR6843ISK-ODS [103]	3D Enhance voxel	Dual-View CNN (DVCNN) model

MATLAB Radar ToolBox

https://www.mathworks.com/help/radar/index.html?s_tid=CRUX_topnav

https://www.mathworks.com/discovery/point-cloud.html

MATLAB mmRadar Wave Hardware Support

https://www.mathworks.com/help/radar/ug/getting-started-timmwaveradar-example.html