A Practical Toolbox for Getting Started with mmWave FMCW Radar Sensors

Manfred Constapel*, Marco Cimdins* and Horst Hellbrück*†
* Technische Hochschule Lübeck, Germany
Department of Electrical Engineering and Computer Science
Email: {manfred.constapel, marco.cimdins, horst.hellbrueck}@th-luebeck.de
† University of Luebeck, Germany,
Institute of Telematics

***Abstract*—In this paper, we sum up our experience gathered working with mmWave FMCW radar sensors for localization problems. We give a glimpse of the foundations of radar that is necessary to understand the benefit and advantages of this technology. Moreover, we introduce our open-source software toolbox *pymmw* based on Python for Texas Instruments IWR1443 ES2.0 EVM sensors to provide students and researchers easy access to those radar sensors. In doing so, one can jump right into sensing with mmWave FMCW radar from a practical point of view and start doing experiments and developing own applications. Finally, *pymmw* is used for data acquisition of a scene illuminated by three virtual radars in three different states of occupancy showing the potential of mmWave FMCW radar for indoor and distance-based localization applications.**

***Index Terms*—radar, sensing, fmcw, mmwave, localization**

I. Introduction & Radar Principles

In this paper, we introduce the open-source software toolbox *pymmw* in order to get the reader started with mmWave FMCW (frequency modulated continuous wave) radars for indoor localization. Recently, commercial off-the-shelf mmWave FMCW radar sensors are available for less than 500 Euro, therefore become interesting for a wide range of applications such as indoor localization and tracking.

mmWave is the band of spectrum between 30 GHz and 300 GHz. This technology is insensitive against environmental influences such as smoke, fog, rain, bad light, and extreme temperatures. FMCW mmWave radar can do range measurements with high accuracy (less than 1 mm) and detect very fine motions while it can penetrate through materials like plastic, fabric, and drywall.

Commonly FMCW radars use some form of linear frequency modulation, e.g. sawtooth. The continuous transmission of the signal often is organized into loops (or packets). Each loop consists of a series of linearly frequency modulated fragments, called chirps, which swipe the bandwidth B in the time interval T, which is often referred to as the Coherent Processing Interval (CPI), with slope m as shown in Figure 1. The transmitted chirp (TX) gets reflected off a target, and a time-delayed version of the chirp (RX) is received by the radar. The round-trip time of the chirp corresponds to the distance to the target, which can not be measured directly, instead, the received chirp is mixed, hence multiplied, with the signal being transmitted yielding the frequency difference f_B. The frequency difference f_B over time constitutes a frequency tone, which reveals after transformation to the frequency domain by Discrete Fourier Transform (DFT), e.g. utilizing the Fast Fourier Transform (FFT), a beat frequency, thus a peak in the frequency spectrum. The peak corresponds to the distance of the target at a given maximum range R_{max}.

For the sake of simplicity, and due to the focus on distance-based localization, this paper is confined to distance estimation only. Thus, velocity and angle estimations are not considered, which can be assumed being subsequent processing steps of range estimation. Nevertheless, mmWave FMCW radar is in general very capable of doing high-precision radial velocity measurements by exposing Doppler shifts [1], and, utilizing and virtually combining an array of RX and TX antennas in a MIMO configuration [2], able to estimate the angle of arrival in elevation and azimuth via beamforming techniques.

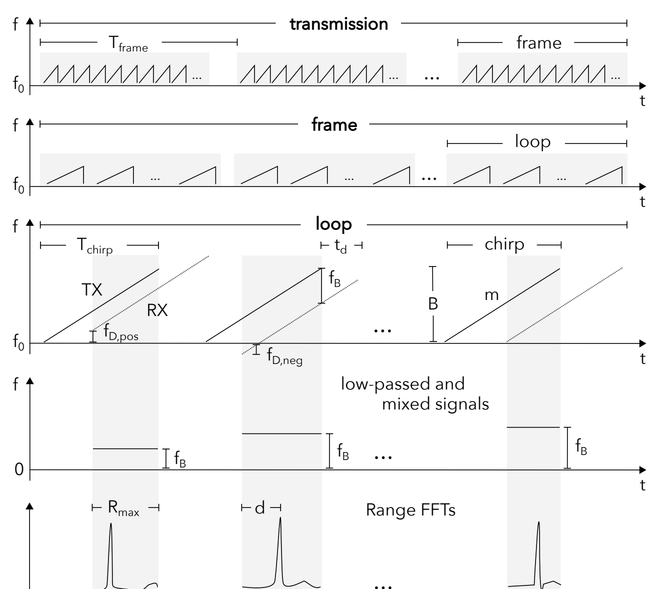

Fig. 1: Relationship between frames, loops, and chirps (upper half) and processing steps commonly used in FMCW radar (lower half)

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II. Related work & Further Reading

This section provides a few references for further reading and more in-depth information for research.

[3] gives a classical overview of the radar data processing pipeline. It covers signal models, sampling, waveforms, Doppler and detection processing as well as beamforming. [4] reveals details about the techniques used for radar systems with distributed antennas, hence defining MIMO as a distributed system, from different angles of view: localization, adaptive signal design, and space-time coding. [5] provides a comprehensive theoretical and analytical background in reasonable depth to modern radars. It starts with different variants of the radar equation and ends up with several loss factors that should be kept into account while estimating ranges with radar. [6] focuses on signal processing, in particular on the difference frequency signal (DFS) for short-range FMCW applications in industrial environments. [7] describes methods for filtering, e.g. with Kalman filters, and tracking of multiple moving and maneuvering targets one would expect to see in air surveillance applications. Furthermore, it evaluates aspects of the radar data processing pipeline and introduces simulation concepts for radar data processing. [8] captures a large variety of indoor monitoring applications for daily living utilizing FMCW radar and CSI- or RSSI-based DFL systems. It focuses on monitoring and classification of motion activities of humans at home for elderly monitoring or in hospitals for vital signs monitoring. [9] describes the principle of a circuit for a constant false alarm rate (CFAR). CFAR schemes vary the detection threshold as a function of the sensed environment to detect targets.

III. Getting Started

In this section, the ingredients needed to immediately jump into experimenting with mmWave FMCW radar sensors are briefly introduced.

1) mmWave Sensor: In essence, the IWR1443BOOST evaluation board from Texas Instruments [10] provides everything needed to start developing radar applications on a low-power ARM Cortex-R4F processor. It provides plenty of interfaces as well as onboard emulation for programming and debugging. The device got a small form factor and operates at 76 GHz to 81 GHz while having low power requirements - consumption is regularly less than 0.5A of DC current. It can get up to, depending on the RF frontend configuration, 12 virtual antennas (3 TX $\times$ 4 RX) for aperture, which provides a reasonable resolution in azimuth and elevation for various indoor monitoring and tracking applications.

2) mmWave SDK: The mmWave software development kits (mmWave SDKs) contain firmware for the Radar Subsystem (RadarSS or BSS) and Master Subsystem (MSS) - called Labs or Demos respectively - of supported mmWave FMCW radar devices from Texas Instruments. mmWave SDKs come in two flavors supporting different devices: IWR for industrial applications and AWR for automotive applications. They are updated frequently, while the number of contained Demos and Labs increases, and more and more mmWave radar sensor EVMs become supported.

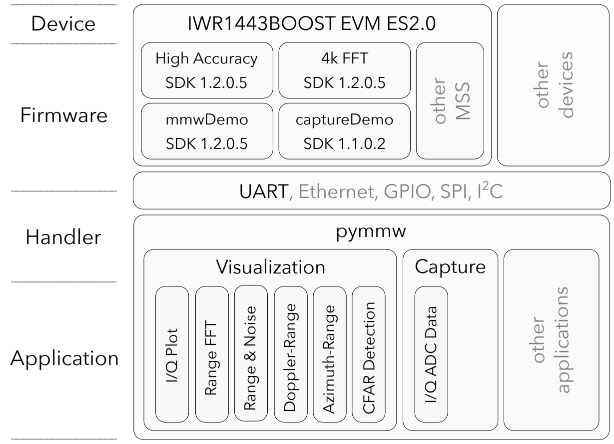

Fig. 2: Building blocks of *pymmw*

3) mmWave Toolbox: pymmw[1] acts as a host for various applications, e.g. I/Q Plot and Range FFT, which can be categorized into plots (visualization) and data aquisition (capture). For both, visualization and capturing applications, data is captured exclusively via two UART channels from a supported MSS except for the *captureDemo*, which performs a direct L3 memory read via the SPI, GPIO and RS233 capabilities of a FTDI chip of the onboard XDS110 debugger utilizing the Debug Server Scripting (DSS) library bundled in Code Composer Studio (CCS). In *pymmw* - at this point in time - four MSS for the Texas Instruments IWR1443 ES2.0 evaluation board from SDK 1.2.0.5 and SDK 1.1.0.2 are supported. Applications in *pymmw* are imported dynamically, and while running multiple applications in parallel, they are executed in different processes using pipes for interprocess communication (IPC). Hence, being in a separate process, an application does not affect other applications in execution to a great extent, i.e. complex post-processing can be done alongside a visualization with costly rendering threads in pseudo-realtime.

IV. Example Application

In this section, the potential of the mmWave radar in a simple indoor localization scenario is briefly shown by an example application, aiming to detect and localize targets within an area of interest or scene respectively. The example is inspired by an application that is driven by a device-free-localization system [11] developed in our institute.

Three mmWave radars [10] are placed in a triangular pattern at 1.37 m in height in an indoor corridor as shown in Figure 3. The task is to observe the area of interest in order to sense the presence of a target and estimate its position.

Approximately 500 measurements, i.e. Range FFTs, are taken with *pymmw* from each radar fixed at locations R_1, R_2 and R_3 illuminating the scene at three different states of occupancy: 1) idle, hence no target is located in the scene, 2) an octahedral corner reflector - composed of 12 isosceles triangles covered

[1] M. Constapel, "Pythonic mmWave Toolbox for TI's IWR Radar Sensors", https://github.com/m6c7l/pymmw, 2019.

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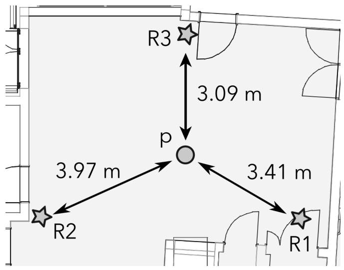

Fig. 3: Indoor measurement setup with radar locations R_1 to R_3 and corresponding distances d_1 to d_3 to target location p

with aluminum foil, 7 cm in length at side edges - is placed at the position p, and 3) an adult is standing at the position p. The radars are equipped with the mmwDemo MSS firmware of SDK 1.2.0.5 and are configured to transmit in temporally separated slots to avoid interference with other radars.

The most important RF configuration parameters applied to all radars are depict in Table I.

TABLE I: Radar RF configuration for scene illumination

Parameter	Value	Parameter	Value
f_0	77 GHz	P_{frame}	100 ms
m	50 MHz/μs	$\#chirps/frame$	32
B	3.6 GHz	$\#loops/frame$	16
$\#RX$	4	$\#samples/chirp$	144
$\#TX_\phi$	2	R_{max}	480 cm
$\#TX_\theta$	0	ΔR	4.2 cm

From the measurements of the idle state the mean value $\overline{r}_{\text{idle}}$ is estimated in order to remove clutter in the measurements of the other states having a target, either a reflector or an adult, placed the scene. For the detection of both, reflector and adult, a very simple peak detection algorithm is used that determines the absolute maximum in the Range FFT of a given measurement series. The principle idea is to calculate the difference Δr between the idle state and observation $\Delta r = r_{\text{target}} - \overline{r}_{\text{idle}}$ and find the peak that correlates to the obstacles $\hat{r} = \arg\max(\Delta r)$.

After the peak detection, the Euclidean distance between the ground truth distance r and the distance at the peak of the difference $\hat{r}$ is calculated in order to estimate μ_{error} and σ_{error}.

TABLE II: Results regarding reliability of the simple peak detection algorithm in the Range FFTs

	Reflector			Adult		
	R1	R2	R3	R1	R2	R3
μ_{error} [cm]	0.02	4.32	0.19	7.67	22.65	78.70
σ_{error} [cm]	0.00	0.00	0.00	3.75	66.70	110.21

The results are shown in Table II. The mean as well as the standard deviation for the reflector are less than 4 cm, which is a great result for device-free indoor localization systems. The result for the adult shows the potential of mmWave radar for localization by an offset of approximately 8 cm and a deviation of about 4 cm for R_1. The results for R_2 and R_3 are worse, however, this is quiete likely due to the simple peak detection algorithm we employed averaging noisy peaks which are not related to the adult. Furthermore, in comparison to the adult, the reflector provides a huge increase in the effective radar cross section (RCS) at a relatively small space. Therefore, considerable amounts of energy get reflected off from a virtually single point, thus the received signal is less noisy.

V. Conclusion & Future Work

This paper provide a quick start guide for mmWave FMCW radar sensors. It illustrates details about the foundations of radar that is necessary for creating distance-based localization applications. The open-source software toolbox *pymmw* based on Python provides students and researchers easy access to Texas Instruments IWR1443 ES2.0 EVM sensors and enables them getting started immediately. To demonstrate the ease of use and to show the potential of mmWave FMCW radar for indoor localization applications, *pymmw* is used in an example application involving three radars and three states of occupancy for capturing data for post-processing purpose.

In the future, support for more mmWave radar sensors and the attachable DCA1000EVM capture card will be added, to enable easy high-speed capturing of radar cube data (RDC) in pseudo-realtime via Ethernet with *pymmw* in order to employ machine learning techniques and methods of artificial intelligence for more advanced detection algorithms and filters.

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