Introduction to automotive FMCW Radar Technologies

Using Texas Instruments mmWave AWR sensor series

Jan Luca Uphoff
I hereby declare that the thesis

**Introduction to automotive FMCW Radar Technologies**

is my own unaided work and all experiments are the result of my own research. Any further source is identified and referenced.

Karlskrona, June 4, 2018

Jan Luca Uphoff
This thesis is submitted to the Department of Applied Signal Processing at Blekinge Institute of Technology in partial fulfillment of the requirements for the degree of Bachelor of Engineering in Electrical Engineering. The thesis is equivalent to 10 weeks of full time studies.

Contact Information:
Author: Jan Luca Uphoff
E-mail: juphoff@stud.hs-bremen.de

1. Supervisor:
M.Sc. Muhammad Rameez
E-mail: muhammad.rameez@bth.se
Department of Mathematics and Natural Science

2. Supervisor:
Ph.D. Mattias Dahl
E-mail: mattias.dahl@bth.se
Department of Mathematics and Natural Science

3. Supervisor:
Ph.D. Mats Pettersson
E-mail: mats.pettersson@bth.se
Department of Mathematics and Natural Science

Examiner:
Ph.D. Sven Johansson
E-mail: sven.johansson@bth.se
Department of Applied Signal Processing

Faculty of Computing
Blekinge Institute of Technology
SE–371 79 Karlskrona, Sweden

Internet : www.bth.se
Phone : +46 455 38 50 00
Fax : +46 455 38 50 57
Abstract

The goal of the following thesis is to transfer radar basic theory in a practical work using Texas Instrument’s mmWave radar series. The range of practical applications for FMCW radars has increased, for example in automotive sector.

Understanding the basics of radar mathematics in a simplified way, as well as the transfer from theory to practical work is important for any engineer working on radar projects. Even if the theory is known, the way from a theory to a running system can be hard, facing several problems, because the reality is limited. In two experiments, data from the radar is collected while cars are crossing the observation area of the radar. The data is then used to count the number of vehicles passing the observation area and to estimate the movement of the objects in the field of view.

Keywords: Short Range Radar, Automotive Wave Radar, FMCW Radar, Texas Instruments AWR.
**Contents**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>i</td>
</tr>
<tr>
<td><strong>1 Introduction</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Context and Motivation</td>
<td>1</td>
</tr>
<tr>
<td><strong>2 Radar Fundamentals</strong></td>
<td>2</td>
</tr>
<tr>
<td>2.0.1 Basics</td>
<td>2</td>
</tr>
<tr>
<td>2.1 Theory</td>
<td>3</td>
</tr>
<tr>
<td>2.1.1 Distance and Radial Velocity Measurement</td>
<td>3</td>
</tr>
<tr>
<td>2.1.2 Angular Measurement</td>
<td>4</td>
</tr>
<tr>
<td>2.1.3 FMCW Radar Operation</td>
<td>5</td>
</tr>
<tr>
<td>2.1.4 FMCW Radar Components</td>
<td>8</td>
</tr>
<tr>
<td>2.1.5 mmWave technology</td>
<td>9</td>
</tr>
<tr>
<td>2.2 Antenna Configuration</td>
<td>10</td>
</tr>
<tr>
<td>2.2.1 Antenna Arrays</td>
<td>10</td>
</tr>
<tr>
<td>2.2.2 MIMO</td>
<td>13</td>
</tr>
<tr>
<td><strong>3 Experiment preparation</strong></td>
<td>14</td>
</tr>
<tr>
<td>3.1 Texas Instruments mmWave products</td>
<td>14</td>
</tr>
<tr>
<td>3.2 Connecting to a PC</td>
<td>15</td>
</tr>
<tr>
<td>3.3 Available Demos</td>
<td>15</td>
</tr>
<tr>
<td><strong>4 Step by step setup guide</strong></td>
<td>16</td>
</tr>
<tr>
<td>4.1 Flashing the memory</td>
<td>16</td>
</tr>
<tr>
<td>4.2 AWR1642 demo visualizer</td>
<td>21</td>
</tr>
<tr>
<td><strong>5 Experiment</strong></td>
<td>23</td>
</tr>
<tr>
<td>5.1 Object Movement</td>
<td>24</td>
</tr>
<tr>
<td>5.2 Object Counting</td>
<td>24</td>
</tr>
<tr>
<td>5.3 Setup</td>
<td>25</td>
</tr>
<tr>
<td>5.4 Results</td>
<td>26</td>
</tr>
</tbody>
</table>
6 Analysis and Discussion

6.1 Object Movement .................................................. 27
6.2 Object Counting ..................................................... 29

7 Conclusion .................................................................. 31

Image Licenses ................................................................ 33

References ...................................................................... 34
### List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>AoA</td>
<td>Angle of Arrival</td>
<td>1</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog Digital Converter</td>
<td>8</td>
</tr>
<tr>
<td>AWR</td>
<td>Automotive Wave Radar</td>
<td>1</td>
</tr>
<tr>
<td>BTH</td>
<td>Blekinge Tekniska Högskola</td>
<td>25</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
<td>31</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital Analog Converter</td>
<td>8</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
<td>8</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
<td>9</td>
</tr>
<tr>
<td>EVM</td>
<td>Evaluation Module</td>
<td>14</td>
</tr>
<tr>
<td>FMCW</td>
<td>Frequency Modulated Continuous Wave</td>
<td>5</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
<td>14</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
<td>6</td>
</tr>
<tr>
<td>IWR</td>
<td>Industrial Wave Radar</td>
<td>14</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
<td>8</td>
</tr>
<tr>
<td>LVDS</td>
<td>Low Voltage Differential Signaling</td>
<td>31</td>
</tr>
<tr>
<td>MCU</td>
<td>Microcontroller Unit</td>
<td>8</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
<td></td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
<td>10</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
<td>8</td>
</tr>
<tr>
<td>SDK</td>
<td>Software Development Kit</td>
<td>15</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single Input Multiple Output</td>
<td>13</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interface</td>
<td>31</td>
</tr>
<tr>
<td>TI</td>
<td>Texas Instruments</td>
<td>1</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Context and Motivation

Currently, there is a lot of progress going on in autonomous driving technologies and the implementation of these in today’s vehicles. These technologies will even develop faster, if a lot people can access it for a cheap price, e.g. Arduino\(^1\). With the Automotive Wave Radar (AWR) series offered by Texas Instruments (TI), which combines a high performance mmWave radar in a small sized single chip, this technology is available for everybody for a price of 299 USD. The main aim of this project is to get a full adjustable radar board to apply some signal processing on the receives radar signal. This will help to develop post processing algorithms for future object detection. The development of algorithms is important to improve autonomous driving in future. Moreover, this thesis can be used as a handbook for everyone to setup this radar board.

\(^1\)Arduino is an open-source electronic development platform. Because of the low price, and all open accessible software and schematics, a huge community has grown.
2.0.1 Basics

Radar stands for radio detection and ranging and basically describes a method of distance measurement between the radar device itself and objects in its field of view [1]. In addition to the distance, the received signal contains targets’ radial velocity information as well. Furthermore, targets’ azimuth and elevation angles can be obtained using various antenna arrangements. Knowing the distance and azimuth angle of a target, the radar’s field of view can be mapped.

The radar spreads electromagnetic waves, these are reflected by objects and will be received by the radar again. In figure 2.1, two antennas are used, one for radiating the waves, the second for receiving the reflections, caused by a car [2]:

![Figure 2.1: Radars transmitting antenna spreads an electromagnetic wave, which is reflected by an object. The reflected wave is received by a second antenna.](image)
Chapter 2. Radar Fundamentals

2.1 Theory

2.1.1 Distance and Radial Velocity Measurement

The distance of a target can be calculated by measuring the time between transmitted and received waves and knowing their speed:

\[ \text{Distance} = \frac{\text{Time Delay} \times \text{Speed}}{2} \quad (2.1) \]

where \( \lambda \) is known as wavelength, \( c \) stands for the speed of light and \( f \) is the frequency. Related to the previous equations, the time delay between transmitting and receiving signal gives information about the target’s distance to the radar:

\[ \text{Distance} = \frac{\lambda}{2f} \quad (2.2) \]

A moving object reflects a transmitted wave with a changed frequency, called doppler frequency, depending on the targets’ moving direction [4]. The target’s radial velocity can be calculated as:

\[ \text{Radial Velocity} = \frac{\lambda}{2f} \quad (2.3) \]

Figure 2.2 shows a radar measuring the radial velocity and the distance of a moving target. The radial velocity together with the angle leads to the velocity of the target.

Figure 2.2: Moving object with a specific velocity. Distance and radial velocity is measured by the radar.
2.1.2 Angular Measurement

The capability of a radar to estimate the angle of the targets helps in mapping the targets accurately in the field of view of the radar. Angle of Arrival (AoA) of a target is estimated by measuring the phase shift in the received signal. The initial phase of the receiving signal can be calculated as following:

$$\Delta \Phi = 2\pi f \Delta \tau$$

$$\Delta \Phi = \frac{4\pi \Delta r}{\lambda}$$

(2.4)

Where $\Delta \Phi$ is the complex signals phase, $f$ the frequency, $\Delta \tau$ the time difference between two receiving antennas, $\Delta r$ the distance difference between two receiving antennas and $\lambda$ the wavelength.

The Angle of Arrival $\Theta$ of an object in the field of view of the radar can be calculated from a small angular difference $\Delta \Phi$ between two receiving antennas as following:

$$\Theta = \sin^{-1} \left( \frac{\lambda \Delta \Phi}{2\pi l} \right)$$

(2.5)

where $l$ describes the distance between the antennas. Further details regarding multiple receiving antennas is discussed in the next chapter.
2.1.3 FMCW Radar Operation

Radars use various types of wave forms for detection. The Frequency Modulated Continuous Wave (FMCW) radar waveform is currently being used in automotive applications [5]. FMCW radars enable continuous range measurements and achieve much greater power efficiency than pulse based radars. Simultaneous range and velocity measurement is done by transmitting multiple FMCW chirps. Instead of only one frequency, a frequency chirp with a linear slope s, a center frequency $f_c$ and a bandwidth $B$ is used as shown in figure 2.3. The slope is dependent on the bandwidth and the time $T$ between two chirps.

With the given information we can create the frequency function over time [5]:

$$f_T(t) = f_c + \frac{B}{T} t$$  \hspace{1cm} (2.6)

The general frequency function is used to develop the phase function over time [5]:

$$\Phi_T(t) = 2\pi \int_{T}^{t} f_T(t) \, dt$$  \hspace{1cm} (2.7)

$$\Phi_T(t) = 2\pi \left( f_c(t) + \frac{1}{2} \cdot \frac{B}{T} t^2 \right) - \Phi_T_0$$  \hspace{1cm} (2.8)
The phase of the down converted signal, which is obtained by combining the transmitted and the received signal, is calculated as [5]:

\[(2.9)\]

\[(2.10)\]

Assuming a target moves with a constant velocity and substituting with \(d\) as distance to the radar leads to following equation [5]:

\[(2.11)\]

\[(2.12)\]

The last part of the term is known as Range-Doppler-Coupling phenomena and can be neglected [5].

\[(2.13)\]

The equation above already contains the Intermediate Frequency (IF) we obtain by filtering the mixed signal with an lowpass filter. After which the desired signal may be calculated as:

\[(2.14)\]

\[(2.15)\]

Where \(f_d\) is the doppler frequency and \(f_b\) is the beat frequency With the calculation of the equation [2.14], the received base band signal can be calculated:

\[(2.16)\]

As shown in equation [2.15], the Intermediate Frequency consists of the doppler frequency \(f_d\) and the beat frequency \(f_b\). The doppler frequency is shown in figure [2.3] and represents a frequency shift between transmitted and received signal.
Combining the range detection and velocity detection, a so called Range-Doppler-Map can be generated to get an overview over several detected objects at different distances with different velocities. An example of a Range-Doppler-Map is shown in figure 2.4. On the x axis a range scale and on the y axis a velocity scale can be found. Each black square describes an object with the specified velocity and range. It is important to mention, that a doppler Fourier transform can only be applied on saved data frames and is part of post processing [4]:

Figure 2.4: Range-Doppler-Map
2.1.4 FMCW Radar Components

Following components are necessary for radar measurement [5]:

- High-speed Digital Analog Converter (DAC) and signal generator synthesizing a waveform in a specific frequency, which then can be transmitted using an antenna.
- Transmitting and receiving Antenna with specific sizes regarding to the wavelengths for improved gain
- Low Noise Amplifier (LNA) to increase the signal power
- Fast Analog Digital Converter (ADC) to measure and digitize the receiving signal
- Frequency mixer to measure rearrangement of transmitting and receiving signal
- Lowpass filter to get relevant information from the received signal
- A Microcontroller Unit (MCU) to perform Fourier transform and access interfaces for further data processing.

A Radio Frequency (RF) signal is synthesized and transmitted as electromagnetic wave in a specific direction. This signal is reflected back after collision with an object and is received at the receiving antenna. The power of this signal depends on the objects distance and its reflection properties. Since the power of the received signal is very low, an Low Noise Amplifier is used to increase the signal power. In a next step a mixer is used to combine the transmitted and received signal. A low pass filter is then used to extract the base band signal (IF signal) from the mixed signal. Afterwards the analog signal is converted in discrete values using an ADC and digitally post processed using a Digital Signal Processing (DSP) chip or a Microcontroller Unit to send the received signal to other processors using special interfaces. Figure 2.5 shows a block diagram for the signal flow and the single antenna components. The power reduction by -3dB by the power divider leads to a signal with exactly half of the original signals power. Mixed with the maximal received signal this leads to the power of the original signal by multiplication. Amplifiers are used to set the signals to specific ranges.
2.1.5 mmWave technology

In 2009 the European Telecommunications Standards Institute (ETSI) released the specification ETSI EN 302 264-1, which allows short range radars in the frequency band from 76 GHz to 81 GHz for civil purpose. This leads to the fact, that today’s automotive industries use this frequency band for advanced driver assistance systems as preliminary to autonomous driving [6]. The given frequency leads to a wavelength of approximately 4mm, and enables detection of movement within a fraction of millimeters. Therefore, high-frequency, high-energetic radar waves for precise object and movement detection [3]. Summing up, mmWave radar technology uses electromagnetic waves with wavelength in the millimeter range. This enables to use small antennas and high frequencies of several GHz, which makes highly accurate distance measurements possible.

Figure 2.5: Blockdiagram showing the radar components starting in the upper left corner.
2.2 Antenna Configuration

There are various antenna configurations existing for different cases of usage. The detailed description of all of these would exceed the scale of this work. Therefore, the priority is on antenna configurations for mmWave technologies. In this area, mainly reflector, lens and horn antennas are used, but also printed microstrip patch arrays\[7\]. The emphasis on the latter ones as they were used with the TI sensors, which are discussed later. The main interesting thing about these antennas is, that they were designed within the Printed Circuit Board (PCB) manufacturing process. This antenna has a lot of disadvantages regarding the loss and mechanical tolerances. However, an advantage is its minimal size and its ability to operate in open structures makes it attractive for several cases of usage. Another advantage is the ability to put this kind of antenna into fields with several unconnected antennas. Such a configuration is called antenna array.

2.2.1 Antenna Arrays

Antenna arrays can be formed by combining single antenna elements in various geometrical arrangements. Figure 2.6 shows the most common arrangements for antenna arrays\[7\].

Figure 2.6: Different typical ways to arrange antenna arrays in the three dimensions. Each square is an single, unconnected antenna and the lines show the coordinate system. there is no physical connection between the antennas.
Chapter 2. Radar Fundamentals

The most typical arrangements are the linear and planar arrays. Linear antenna arrays can only be used for horizontal angle measurement only. Planar arrays instead can measure vertical and horizontal angle, which enables a three-dimensional measurement with distance, azimuth and elevation. Circular and conformal array arrangements are for more special use cases. We concentrate on the linear array configuration, in which several radiating element are in a single line, not connected. Connecting the radiation elements, they can be seen as a single antenna again. Every radiating element has its own radiation pattern and the values from each element in the pattern consist of an amplitude and phase value. Regarding the amplitude, the values will not differ, because over a distance of several meter, an antenna space of only a few millimeter is not recognizable. Nevertheless, the phase shift between the antennas is measurable and gives information about the targets angle towards the radar. If we now think about an object in an infinitive distance to the radar, the reflected waves can be assumed to be parallel. This helps to calculate the electric field pattern in the far distance field:

\[
E_A(\Phi) = e^{j\frac{2\pi r_0}{\lambda}} \cdot \sum_{N} A_n e^{j\frac{2\pi}{\lambda} n\Delta x (\sin \Phi \sin \Phi_0)}
\]  

(2.17)

where:

- \( N \) = Number of radiating elements
- \( r_0 \) = Distance for the center of the array to the far field observation point
- \( A_n \) = array element amplitude weighting coefficient
- \( \Phi \) = beam pointing, referenced to broadside (\( \Phi = 0 \))
- \( \Delta x \) = the array element spacing
- \( \lambda \) = wavelength
- \( \Phi_0 \) = the desired beam scan angle

In this equation we can see, the electric field depends on two factor. The first factor in front of the sum is called Isotropic Element Pattern, the second factor (all from the sum) describes the Array Factor. As expected, a linear array of radiating elements will increase the amplitude of the received signal. The distance between each radiation object is constant and should not be greater than \( d = \lambda/2 \). Otherwise, the sidelobes instead of the mainlobe will increase [7]. Adding more elements increases the aperture size which in turn enhances the angular resolution [7].
Figure 2.7: Received signal from several antennas close to each other can be assumed as parallel beams. Because of a phase difference between the received signals, a distance which leads to the Angle of Arrival can be calculated.

In figure 2.7 a configuration with several receiving antennas is shown [8]. Comparing the received signals, these will be nearly identical. Each received signal is a complex wave with the same amplitude, frequency and Angle of Arrival, but the complex argument is different. Assuming the source of this signal to be in an infinite distance, the beams will be parallel. This leads to the fact, that a wave received by the first antenna has a slightly different distance to travel then the signal received by the second antenna, as shown in 2.7. Compared to the first receiving antenna, the additional distance for to the second receiving antenna is , while the additional distance to the third receiving antenna is and so on. Because of this small change of distance, there will be a small difference in the time as well, which changes the angular argument of the complex signal. Comparing the the complex arguments, we can calculate the distance difference the beam has traveled to each receiving antenna. Knowing the distance between the receiving antennas, which is constant, the angle between the radar and the target can be calculated.
Chapter 2. Radar Fundamentals

2.2.2 MIMO

Using one transmitting, and receiving antennas (Single Input Multiple Output (SIMO)), the Range-Doppler-Map becomes a multidimensional map and the object identification and localization will increase with the number of receiving antennas [7]. Performing an Fourier transform over dimensions, while the distance between each antenna is known, an angular information can be calculated from the phase shift of the receiving signals. Instead of only increasing the receiving antennas, the number of transmitting antennas can be increased, adding virtual receiving antennas. Comparing radars with two transmitting and four receiving antennas (2x4 MIMO) to radars with one transmitting and eight receiving antennas (1x8 SIMO), the accuracy is similar, but the required space is less, because virtual receiving antennas are added [9]. Figure 2.8 shows SIMO and MIMO radars with their different amount of sending and receiving antennas.

![Different Antenna Configurations](image)

Figure 2.8: Different Antenna Configurations

Using an FMCW radar with mmWave technology and up to three transmitting and four receiving antennas (3x4 MIMO), enables TI's AWR series to measure angle, velocity and range of several objects in a design not bigger than a few centimeter. It is important to mention, that velocity and angle can only be calculated in post processing, while for the range live data can be used.
Chapter 3

Experiment preparation

For the project Texas Instruments mmWave radar series was used for practical experiments.

3.1 Texas Instruments mmWave products

Texas Instruments provide a good range of short range radars using mmWave technologies. They offer two different series of wave radars:

- Industrial Wave Radar (IWR)
- Automotive Wave Radar (AWR)

The main difference of these both series are the use cases. While the IWR used for short ranges with better solution and low velocities, the AWR series is designed for highly dynamic measurements with decreased resolution. Regarding there website, the AWR series is able to detect objects in a distance up to 80m and a velocity of 300km/h, while the IWR series is able to detect a range up to 60m and a velocity of up to 100km/h.

This work deals with operating experience using a sensor out of the AWR series. These series consist at the moment of three products, AWR1243, AWR1443 and AWR1642. Each of the sensors are available as Integrated Circuit (IC) only or as Evaluation Module (EVM), which combines the IC antennas, power supply and connection interfaces on a development board. For this thesis the AWR1642 EVM is used. The main difference between those is the on board DSP provided by the AWR1642, while the AWR1243 needs an external DSP. Further information regarding the differences of TI sensors in the mmWave series can be found in online [10].

3.2 Connecting to a PC

Before starting experiments and investigation of the results, some software have to be installed on the local machine to access the Evaluation Module. First, the requirements for the AWR1642, because only use can operate as standalone. This is based on the fact, that only the AWR1642 has a on board CPU and serial converter. For all other boards, the data can only be accessed by connecting the board to the development kit as well as the TSW1400, which enables high speed data capture. The AWR1642 EVM comes with a pre-flashed cortex-R4F ARM Controller. Out of the box the demo visualizer program is flashed on the controller. Since TI offers a web application, only the TI Cloud Agent Application and a browser plugin needs to be installed to run the application. Texas Instruments recommends the use of Google Chrome.

Other programs can also be flashed to the ARM Core. The steps are described in the SDK user guide \[11\]. As of my current study and observations made, the following programs are necessary:

**Running AWR1642 standalone:**

- Uniflash by TI to flash the ARM Core
- TeraTerm to setup a UART Connection (baudrate115200)
- mmWave Software Development Kit (SDK) for sample programs and instructions
- TI Cloud Agent for the connection between the hardware and the web application

3.3 Available Demos

Texas Instruments provides some demo programs to get started quickly with the radar boards. For the AWR1243 a software called mmwaveLink, which is used to program radar settings using the EVM together with the development package. For the AWR1642, two demo programs available, the visualizer demo and the driver vital signs demo. The visualizer demo is preflashed from factory to provide easy setup and stream specific data for visualization to a local PC. The driver vital signs demo is an example of how this radar could be used to measure the drivers breathing and heart beat if the radar is installed in front or behind the driver. This project focuses the visualizer demo as base to further data processing.

\[2\] Without the development pack, the AWR1243 can not be used to do any settings or measurements.
Chapter 4

Step by step setup guide

4.1 Flashing the memory

Before running any demo application, TI recommends to flash the EVM memory (the pre-flashed memory could contain errors). Therefore, a jumper has to be added to the hardware. In Figure 4.1 the whole Evaluation Module is shown and in figure 4.2 the radar is shown on its attachment and the additional SOP2, which is yellow, is marked with a white circle. This will change the electrical circuit for the SOP headers shown in figure 4.3. Power the board, connect it to the computer via USB and wait for the drivers to become installed. Start the software Uniflash, choose your Board and go to Settings & Utilities and change the COM port to the COM port according the XDS110 Class Application/User in Windows device manager. Figure 4.4 shows the powered radar bard with the connected USB interface. The lighted LEDs are power indicators. Figure 4.5 shows the port identification using the Windows device manager and figure 4.6 shows the settings tab of the Uniflash software, where the COM part has to be changed. Choose a .bin file you want to flash to the memory and load the image to the board. Therefore, figure 4.7 shows the main window of the Uniflash software with the steps which need to be applied to transfer the image, marked and commented in red. The visualizer and capture demo can be found in the SDKs data path. An error could occur, if the wrong port is chosen, or another application is connected to the port.

With the new image flashed on the memory, restart the board without the extra jumper on SOP2. Figure 4.8 shows the reboot of the board with the removed jumper and its previous position marked in white circles.
Chapter 4. Step by step setup guide

Figure 4.1: AWR1642 Evaluation Module with AWR1642 IC antennas, controllers and connection interfaces

Figure 4.2: AWR1642 EVM with extra jumper on SOP2 for programming purpose. The jumper is marked in yellow
Figure 4.3: Electrical schematic for the jumper connections. Marked with a red circle is jumper SOP2, which has to be connected for flashing.

Figure 4.4: Connecting power supply and USB. The power LED lights up to show the board is powered. The power adapter is not included, but specifications are given with 5V and 3A.
Figure 4.5: Using the windows device manager, the used COM ports can be found. The COM port number is important for flashing and for the visualizer setup.

Figure 4.6: Inside Uniflash the COM port has to be changed to the COM port used by the computer. Not changing the port will throw back an error.
Figure 4.7: Steps for Uniflash: First we change the COM port as described before. Then the image, which should be flashed on the CPU is chosen and by clicking "Load Image" transferred to the AWR1642. In the console the transfer progress and later the success shows up.

Figure 4.8: For using the board the extra jumper on SOP2 is removed and the board is rebooted.
4.2 AWR1642 demo visualizer

To run the visualizer demo application, first flash the AWR1642 (the pre-flashed memory could contain errors, so TI recommends to flash it again). Afterwards, open the web application for the demo visualizer: https://dev.ti.com/gallery/view/mmwave/mmWave_Demo_Visualizer/ To use the application, TI Cloud Agent Application and a browser add-on have to be installed on the local machine. Performing this task as administrator is recommended. Afterwards, the web application will start and the connection to the board has to be established, as shown in figure 4.9. Choose the COM ports as given by the Windows device manager and press configure. Afterwards the application shows the settings in the bottom left corner. If it shows waiting for data like in figure 4.9, the reset button on the board has to be pressed once. Now, the device should be connected like in figure 4.10 and the settings for the board can be changed and sent to the hardware. When this process has finished and the console on the left side does not show any errors, the tab can be changed to show the results as plot. Figure 4.11 shows an example output of the Demo Visualizer with the Range-Angle-Map on the left side and plot with the receiving power towards several distances in the middle. On the right side some settings and other information are shown.

Figure 4.9: Settings for demo visualizer
Chapter 4. Step by step setup guide

Figure 4.10: Sending commands in Demo Visualizer

Figure 4.11: Demo Visualizer
Initially, the goal was to directly access the data on the serial port, but unfortunately this was not possible, even after trying several days. Therefore, the decision to work with the running visualizer demo was made. The main goal was to figure out, which measurements could be possible in this way, led to the first idea to set the visualizer demo to a certain state and take screen captures of the resulting plots. The main focus was on the field of view map, as well as the range velocity map. It was possible to build an application to save the plots as image. In Figure 5.1 the demo visualizer application is shown. marked in green squares the Range-Angle and the Range-Velocity-Map, which were saved as image, are shown.

In addition, some simple image processing functions were applied to create a binary map of the objects, finding the center pixel of each shown object and save the pixel index in an array, together with a time stamp. With this data, two
measurements were performed. The first was to capture the way an object takes through the room, the second was to count the number of object over the time. In both cases the program is looped to capture the screen several times per second.

5.1 Object Movement

The first experiment is about analyzing a target’s movement. Therefore, the pixel index of a detected object is store together with a time stamp. Afterwards, a two dimensional map with all identified object over the time is restored, showing the trace of an object through the field of view. As the time frame for this experiment increases, the result will show a map with all areas covered by the radar. To start this experiment, the AWR1642 with the demo visualizer flashed on the CPU is needed. First the connection from the local machine to the radar has to be established and the demo visualizer has to be set up. Now, the live image can be recorded by starting and stopping the programmed screen recorder manually. Stopping the screen recorder, the program will plot the detected objects over the whole time frame.

5.2 Object Counting

In the second experiment, it was tried to count objects over the time. The idea is, to save the number of all detected objects in the map. If a target like a car will pass by, it will cause a wide area of detected objects. If there is no car passing by, or pedestrians, the number of detected objects is much less. By plotting the number of detected objects over the time, we should get peaks with higher number of detected objects for cars passing by. Additionally, cars can be counted by counting the peaks. Next to the number of objects, we might be interested in their velocity as well. Therefore we use a second screen capture box on the Range-Doppler-Plot. Again, we perform some basic image processing, to filter the detected velocities and generating a black white map with these. Furthermore, we calculate the center pixel and save all center pixel indexes in an array, together with the time stamp. In this way we can search for all velocities occurring at a special time.
5.3 Setup

The experiment was set up on a roundabout traffic next to the Blekinge Tekniska Hogskola (BTH). In this case, cars can pass by the radar in close and far distance, and also pedestrians can cross the field of view. To get valuable result, the experiment was taken in a time frame of ten minutes. To identify the outcome, a video of the whole set up was taken in the same time frame. Running the experiment over a longer time frame helped to observe the radar behavior in several different situations. In figure 5.2 you can see the upper part of the AWR1642 at the bottom of the picture. It is facing the same direction like the camera. In the field of view you see a roundabout traffic with the street in close and far distance. Next to the street is a sidewalk for pedestrians. Marked with red pointers are the ways where cars and pedestrians move.

![Image](image.png)

Figure 5.2: Experiment setup
5.4 Results

After collection of data for over ten minutes, the result in figure 5.3 was obtained. The first figure is an image with 400x400 pixels. Each yellow spot means that an object was detected here. The second figure shows a plot with the detected objects over time. The objects range is between 0 and 65 detected objects, the time range is from 0 to 10 minutes in steps of five seconds.

Figure 5.3: Experiment Results: The upper figure shows the object movement in an 400x400 pixel image and the bottom figure shows the object detection from 0 to 65 objects over an record time of 10 minutes
Chapter 6

Analysis and Discussion

6.1 Object Movement

Knowing the field of view of the radar together with the information that there are cars and pedestrians in several discrete distances crossing the field of view, the object movement map can be divided into specific areas:

Figure 6.1: Experiment Result Interpretation 1: 400x400 pixel image with the detected objects and their position.
In figure 6.1 we can see in the upper part of the map an area with a high point density in vertical direction. In horizontal direction, a specific pattern between the point objects can be recognized. This pattern could refer to the demo visualizer and the image processing, because the image processing only takes the center pixel of the objects observed in the demo visualizer application. On the other hand it might be interpreted, that the information transmitted to the demo visualizer is highly simplified or minimized and all values are rounded to specific values which can be shown. By taking all object pixels instead of the center pixel, the horizontal spaces should be filled up, nevertheless it also shows the capacities of the demo visualizer application. Back to the result interpretation, together with knowledge from the video stream, the recognized pattern can be interpreted as the cars moving in far distance. Regarding figure 5.1 the maximum shown distance is 25 meter in a linear scale. Based on this information, it can be estimated, the far distanced cars cross the radars field of view in about 15 to 20 meters. When the cars leave the roundabout traffic, they are in a distance of about 5 meters to the radar.

The second marked area in figure 6.1 shows the cars crossing in close distance to the radar. The borders on the left and right site regards to the maximum measurement angle of the radar, shown in figure 5.1. The point density in this area is the highest, because a car crossing in this close distance fills nearly the whole angle of view, which we can see in the second experiment result. The straight lines in between the points appear because of the image processing and can be ignored. Based on the maximum distance, it can be estimated, the cars in close distance cross the field of view in a distance of 2 to 5 meters.

The third marked area in figure 6.1 can be identified because of the small vertical gap between the high density point areas. These identified objects regard to pedestrians crossing the field of view. Their distance can be estimated between 1 to 2 meters.
6.2 Object Counting

The result regarding the second experiment can be interpreted by connecting the measured number of detected objects to a specific time to the image in the video at this time:

As shown, each peak in the plot belongs to identified objects crossing the field of view. In figure 6.2 some examples of correlating a time stamp to a video frame are shown. Following objects have been detected in this way (left to right):

1. blue car (small), close distance
2. pedestrian, close distance
3. red car (SUV), far distance
4. black car (transporter), close distance
5. blekinge trafiken bus, close distance
6. silver car (limousine), far distance
7. trailer, close distance
8. black car, far distance

Figure 6.2: Experiment Result Interpretation 1
Chapter 6. Analysis and Discussion

These correlations are only examples, and a lot more could be shown. From these results, the peak is higher for cars closer to the radar, than for those in far distance (compare object 1,3,4,6,8). This refers to the face, that radar waves spread isotropic, which also means, that the power decreases exponentially. The results also show, that cars in close distance, which pass the radars field of view more quickly than those in far distance. In figure 6.2 this is shown with the black boxes (compare object 3,6,8). These boxes show a similar object count over a longer time frame. there is no local peak for these objects, but the objects can be identified. Comparing the reflection of the pedestrian with the reflection of a car close to the radar shows, that the pedestrian is detected as less objects, which refers to the surface size, which is smaller in this case. Special cases in this measurement were the transporter (4), this bus (5) and the trailer (7). These targets were shown with the most objects in the measurement, which refers to the bigger reflecting surface. A very interesting case is the trailer, because it is shown as much more objects than all other objects. This could refer to the discontinuously surface, which makes the trailer reflect the radar waves in more directions. It is important to mention, that this way can be much harder to identify objects, because the objects were not referred to their reflecting power. instead we just use the information about how many objects are detected to a specific time. Also, it is hard to count the objects in this case, because the objects give really different measurement values. An algorithm counting objects by the high peaks in the plot, would probably miss cars in far distance, because the peak level is low and and algorithm detecting lower peaks, might identify the same car several times, because the amount of detected objects stays similar for some time. Also, if we just count the number of detected objects, we might not notice if there are two ore more targets in the field of view. Nevertheless, the experiment showed a good detection by the radar in distances between and , which was chosen for the experiment.
Chapter 7

Conclusion

The aim of this thesis was to get knowledge about radar systems and their practical usage. Therefore, the main idea was just to connect the AWR1642 to a computer and see what possibilities it offers. At this time, the main focus was to capture RAW data from the board, but it turned out, this was not possible without two other devices, the mmWave Dev-pack and the TSW1400. The main problem for the RAW data capturing process is, that a lot of data measured by the board, and it is hard to transfer the data to a computer. On board, the AWR1642 has an Low Voltage Differential Signaling (LVDS) interface, which can be used to transfer the data to a external processor, but this is commonly used for embedded systems. There was no possibility to access this interface by using the available ports on the computer. Next to this, the board owns several inter chip interfaces like Serial Peripheral Interface (SPI), Controller Area Network (CAN) etc., which can only be used to send set up commands to the board, but not for receiving data. The only available interface to connect with a standard computer was USB. But in this case, the data transmitted to the demo visualizer was hardly compressed and probably encoded, and it was not possible to receive useful data over USB by using other applications than the visualizer demo. To sum it up, it is really hard to receive RAW data by a radar like this, because of the mass of data, which cannot be handled with standard interfaces. TI is currently working on an Ethernet solution, which would enable the RAW data capture with standard interfaces. Another difficulty with the radar was to run it inside, because all walls caused a lot of reflections. Nevertheless, in my opinion, the AWR1642 is a great opportunity to get started with automotive wave radars, because of the affordable price. Next to this, there is a forum on TI’s website, where the people can share their experiences with the board and get help by the community and professional TI employees. The board itself has a lot of configurations opportunities as well. running the demo visualizer, a lot of parameters can be set regarding the filed of view, frequency, expected velocities, expected detected objects and a lot more. Another point to mention referring to the experiments is, that it is always difficult to work with post processed, or even obtain data from a plot to get the values. In the experiment the plotted data from the demo visualizer was taken to count

[1] https://e2e.ti.com/support/sensor/mmwave_sensors/f/1023/t/646239 21/04/2018
objects and trace their route over time. For tracing the route, the plotted data was copied and the identified objects were extracted and saved. Afterwards, a new plot with all generated object was generated. This worked very well and the end plot showed a trace with a high density of identified objects in the area where an object moved. When counting objects by taking the range-angle-plot and extracting the identified objects, it was more difficult, because the information about the reflection power was missing. Nevertheless, objects were detected by a peak in the number of detected objects. For basic object detection over several distances this experiment is a good example. For more accurate measurements, the RAW data, or another image for the board together with another web application is absolutely necessary. Because the community is growing and the images and applications can be shared online on TI’s developer platform easily, I could imagine, that new programs and applications for special use cases are already in the development progress.
Image Licenses

Figure 2.1: Sandeep Rao, Texas Instruments (https://training.ti.com/sites/default/files/docs/mmwaveSensing-FMCW-offlineviewing_0.pdf)
Figure 2.5: Charly Whisky (https://commons.wikimedia.org/wiki/File:Bsp2_CW-Radar.EN.png), „Bsp2 CW-Radar.EN“; https://creativecommons.org/licenses/by-sa/3.0/legalcode
Figure 2.3: Charly Whisky (Erstveröffentlichung: Radartutorial) (https://commons.wikimedia.org/wiki/File:Fmcw_prinziple.png), „Fmcw prinziple“; https://creativecommons.org/licenses/by-sa/3.0/legalcode
Figure 2.8: Benjamin Baumgärtner (Benbaum), Tiger66, Tobias Frei (ToBeFree) (https://commons.wikimedia.org/wiki/File:MIMO_SIMO_MISO_SISO_explanation_without_confusion.svg), „MIMO SIMO MISO SISO explanation without confusion“; https://creativecommons.org/licenses/by-sa/3.0/legalcode
References


[6] ETSI. Electromagnetic compatibility and radio spectrum matters (erm); short range devices; road transport and traffic telematics (rttt); short range radar equipment operating in the 77 ghz to 81 ghz band; part 1: Technical requirements and methods of measurement. *ETSI EN 302 264-1*, 2009.


