Study of an automotive radar and its applications in objects' identification and classification

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ABSTRACT

The use of automotive radars has become increasingly common, due to the safety and convenience that its features offer to the user, from the AEB (Automatic Emergency Braking) to the ACC (Adaptive Cruise Control), among many others. There are different types of radars that can be used for different ADAS (Advanced Driver Assistance System) applications, for example long and medium range radars, which can be installed in different positions in the vehicle, since that these assembly data are informed during the radar configuration. The RADAR (Radio Detection and Ranging) device is a complex system that comprises several software modules, each of these modules is responsible for certain detection units. Therefore, this work aims to demonstrate a special radar that comprises some of these software modules, specifically a radar that detects objects and plots their respective positions in space will be used.

1. INTRODUCTION

The development and implementation of automotive RADARs (Radio Detection and Ranging) have become essential during the last decade due its improvement on vehicular safety and performance. Besides its intensely development and studies during the last century focusing on military use, nowadays it became more present in scientific researches and industrial development. The silicon-based solutions for radar development has increased recently and its applications using 24/77-GHz automotive radars, like Adaptive Cruise Control (ACC) and Automatic Emergency Braking (AEB). The automotive radars can be installed around the vehicle to identify objects at close, mid and long range; these mounted radars improve the safety and security of the driver and passengers offering features including parking assistance, lane departure warning, forward collision warning and other driver assistance features [1].

2. RADAR AND DOPPLER RADAR: INVENTION AND HISTORY

The first radar system was created by Sir Robert Alexander Watson-Watt in 1935, but his original concept have been used and adapted by others scientists, physicists and inventors that expanded and improved on it over the years. Watson-Watt, born in Scotland in 1892 and educated at St. Andrews University, was a physicist who worked at the British Meteorological Office and designed devices that could locate thunderstorms in 1917. In 1926, he coined the term "ionosphere" and after that, he was appointed as the director of radio research at the British National Physical Laboratory in 1935 where he completed his research to develop a radar system that could locate aircraft. In April 1935, radar was officially awarded a British patent.

Figure 1. Sir Robert Alexander Watson-Watt. Source: Joubert de la Ferté, Philip [1955]. The Third Service*. London: Thames and Hudson. Plate 18*

Watson-Watt's other contributions include a cathode-ray direction finder that is used to study atmospheric phenomena, research in electromagnetic radiation, and inventions used for flight safety [2].

Another important physicist that also contribute with the radar development was Heinrich Hertz who discovered, in 1886, that an electric current in a conducting wire radiates electromagnetic waves into the surrounding space when swinging rapidly back and forth. Nowadays, we call such a wire an antenna. In his lab, Hertz detected these oscillations using an electric spark in which the current oscillates rapidly. These radio waves were first known as "Hertzian waves". Today we measure frequencies in Hertz (Hz) (oscillations per second) and at radio frequencies in megahertz (MHz).

Figure 2. Heinrich Hertz. Source: Robert Krewaldt, Kaiserplatz 16, Bonn [1890] - Cabinetphotograph, Kabinettfotografie

Hertz was the first that demonstrate experimentally the production and detection of "Maxwell's waves", a discovery that leads directly to radio [2].

Before these two genius, the Scottish physicist James Clerk Maxwell combined the fields of electricity and magnetism to create the theory of the electromagnetic field.

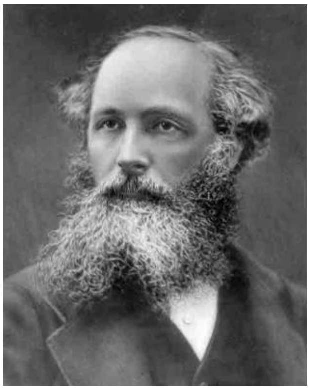

Figure 3. James Clerk Maxwell Source: https://blog.ufes.br/paineleletrico/2015/04/22/james-clerk-maxwell/ [2015]

Maxwell began his career as a professor by filling in the vacant Chair of Natural Philosophy at Aberdeen's Marischal College in 1856. Maxwell went on to become Professor of Physics and Astronomy at King's College in London, an appointment that would form the foundation of some of the most influential theory of his lifetime. His paper on physical lines of force took two years to be written and was ultimately published in several parts. The paper introduced his essential theory of electromagnetism: that electromagnetic waves travel at the speed of light and that light exists in the same medium as electric and magnetic phenomena. Maxwell's 1873 publication of "A Treatise on Electricity and Magnetism" produced the fullest explanation of his four partial different equations, which would go on to become a major influence on Albert Einstein's theory of relativity. Einstein summed up the monumental achievement of Maxwell's life work with these words: "This change in the conception of reality is the most profound and the most fruitful that physics has experienced since the time of Newton."

It is impossible to write about radar creation without mentioning the person who discovered the Doppler radar: the Austrian physicist Christian Andreas Doppler. In 1842, Doppler first described how the observed frequency of light and sound waves was affected by the relative motion of the source and the detector. This phenomenon became known as the Doppler Effect, most often demonstrated by the change in the sound wave of a passing train. The train's whistle becomes higher in tone as it approaches and lower in tone as it moves away.

Figure 4. Christian Andreas Doppler. Source: https://litfl.com/wp-content/uploads/2019/04/Christian-Andreas-Johann-Doppler-1803-1853.jpg [2019]

Doppler determined that the number of sound waves reaching the ear in a given amount of time, called the frequency, determines the tone or pitch that is heard. The tone remains the same as long as you are not moving. As the train moves closer, the number of sound waves reaching your ear in a given amount of time increases and the pitch therefore increases. The opposite occurs as the train moves away from you [2].

3. HISTORY AND RADAR CONCEPTS

In the beginning of its history, it was called RDF (Radio Direction Finder), name given by the British and later, in 1940, it was renamed RADAR by the Americans, as it is known nowadays.

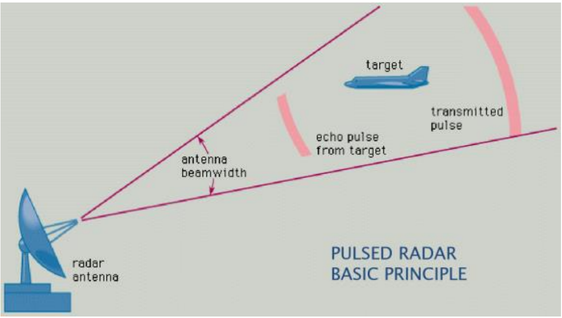

Figure 5.Radar Antenna Pulse. Source: https://www.britannica.com/technology/radar/Transmitters [1994]

Looking at the animal realm, is possible to see that bats have very similar technique to modern radars, such as Doppler, monopulse, chirped signals, but with one particular difference, they are not electronics.

The basic concepts of radar were developed in the late 19th and early 20th centuries. However, radar emerged as a practical engineering device just before and during World War II. On February 12th, 1935, Robert Watson-Watt sent a memorandum entitled "Detection of aircraft by radio methods", which Hanbury Brown calls "the birth certificate of radar" [3].

Radar is an electromagnetic system that can detect and locate objects. It transmits a particular type of waveform and detects the nature of the echo signal, for example: a pulse-modulated sine wave. Radar is used to enhance the sense's capability for observing the environment, especially the sense of vision. However, radar is not a substitute for the eye, but can do what the eye cannot do. The eye gives such details that radar cannot resolve it all, like be able to recognize the color of objects. Nonetheless, radar can be so useful to see through environmental and weather conditions such as haze, fog, darkness, rain and snow. In addition, the radar has the great advantage of measuring the distance or range to the object. This is considered the radar most important attribute [3].

A fundamental form of radar is consisted by an oscillator that generates an electromagnetic radiation and transmit it through an emitting antenna, a receiving antenna and an energy-detecting device, or receiver. A portion of the transmitted signal is intercepted by a reflection object (target) and is reradiated in all directions. The radar is interested in the energy that is reradiated back to it. The returned energy is collected by the antenna and is delivered to a receiver, which processes the signal and detects the presence of the target, extracting its location and relative velocity. The distance to the target is determined by measuring the time taken for the radar signal to travel to the target and back. The direction, or angular position, of the target may be determined from the direction of arrival of the reflected wave-form. The usual method of measuring the direction of arrival is with narrow antenna beams. If there is a relative motion between target and radar, the shift in the carrier frequency of the reflected wave (Doppler Effect) is a measure of the target's relative (radial) velocity and may be used to distinguish moving targets from stationary objects [3].

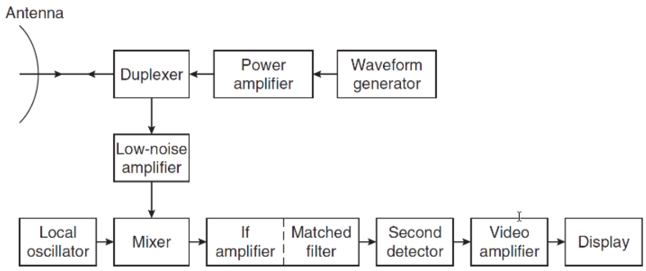

Figure 6. Radar Block Diagram. Source: Skolnik, M.I. Radar handbook - 2nd ed. McGraw-Hill, 1990

The transmitter is one of the basic elements of a radar system. The figure 7 illustrates the relationship between the transmitter, duplexer, antenna, and receiver in a simple radar system.

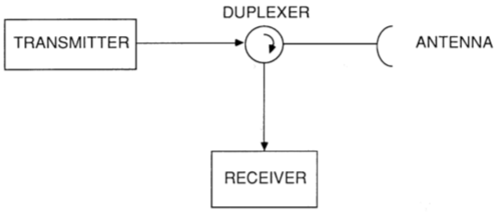

Figure 7. Transmitter relationship. Source: Skolnik, Merrill Ivan. Introduction to radar systems, 1981. McGraw-Hill Book Company

The main functions of the radar transmitter is to generate the peak and average powers required to detect the desired targets. In addition, transmitters must be efficient, reliable and easily maintained, as well as have the wide bandwidth and high power that are characteristic of radar applications [4].

The transmitter generates a radio frequency (RF) signal that may be continuous wave (CW) or pulsed, and its amplitude and frequency are usually designed to fulfill specific requirements of the radar system. The power ratings of radar transmitter range from milliwatts to terawatts, and the power source may be vacuum tube or solid state [5].

The antenna is one of the most important parts of a radar system. It performs essential functions, such as transferring the transmitter energy to signals in space with the required distribution and efficiency and ensuring that the signal has the required pattern in space. Generally, this has to be sufficiently narrow in azimuth to provide the required azimuth resolution. It also concentrates the radiated energy on transmit, collects the received echo energy from the target, provides a measurement of the angular direction to the target and spatial resolution to resolve (or separate) targets in angle, among others [5].

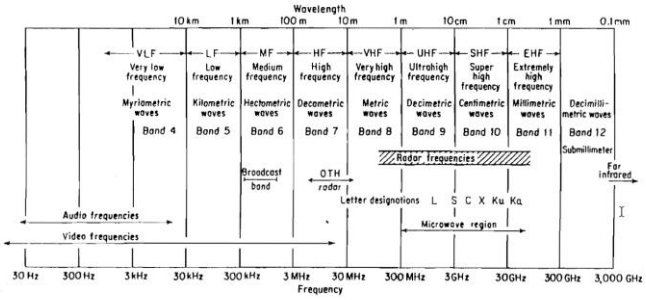

Figure 8. Electromagnetic Spectrum. Source: Skolnik, Merrill Ivan. Introduction to radar systems, 1981. McGraw-Hill Book Company

Therefore, radar transmits a signal with a wavelength and a frequency and independent of its direction, distance, relative speed and direction of the target, which is reflected, can be observed, and the radar equation can be used to calculate the strength of the signal [6].

$$R_{\max} = \sqrt[4]{\frac{P_s G^2 \lambda^2 \sigma}{P_{e_{\min}} (4\pi)^3 L_{ges}}}$$

The equation above looks for the maximum sensor range R_{max}. Then, P_e stands for received signal strength, at the same time P_s denotes the transmitted signal power. The antenna gain is given by G, as well as σ represents the scattering cross section of the reflecting target and λ is the wavelength [6]. The square root with power 4 represents the degradation of the signal strength and the loss factor L_{ges} is considered because when the radar equation is calculated, it useful to assume that the propagation of electromagnetic waves is under ideal conditions [7].

4. FREQUENCY-MODULATED CONTINUOUS-WAVE RADAR (FMCW RADAR) AND THE DOPPLER EFFECT

Although there is no single way to characterize a radar, it can be classified by its architecture. In the automotive area, there are two most relevant classes: Pulse radar and Continuous Wave (CW) radar [1]. The radar signals transmitted as a Continuous Wave can be divided in two categories, unmodulated and modulated frequency (FMCW). This article will focus on the FMCW radars, due its application in this respective project.

The FMCW radar is the most popular in the automotive scenario, due the possibility of change the frequency as required to specific application. This type of radar radiates a continuous wave signal called chirp, which is a pulse that is sent by radar and detect an object, measure its velocity, range and position [8].

Modulated continuous wave radar devices without frequency modulation have the disadvantage of not being able to determine the target range. It happens because the radar lacks the timing mark needed to allow the system to accurately transmit and receive the signal converting it into range. When an echo signal is received, that change of frequency gets a delay Δt (by runtime shift) like the pulse radar technique. In pulse radar, however, the runtime must be measured directly. In FMCW radar, this measurement is done by differences in phase or frequency between the actually transmitted and the received signal instead [9].

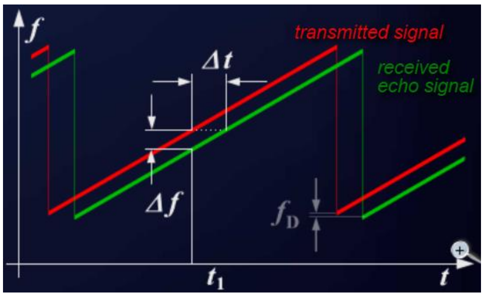

Figure 9. Radar Chirp. Source: https://www.radartutorial.eu/02.basics/Frequency%20Modulated%20Continuous%20Wave%20Radar.en.html [2020]

The basic features of FMCW radar are the ability to measure very small ranges to the target and to the capacity to measure the target range and its relative velocity simultaneously. Other important features of this type of radar are: very high accuracy of range measurement; processing signal after a low frequency range, considerably simplifying the realization of the processing circuits and safety from the absence of the pulse radiation with a high peak power [8].

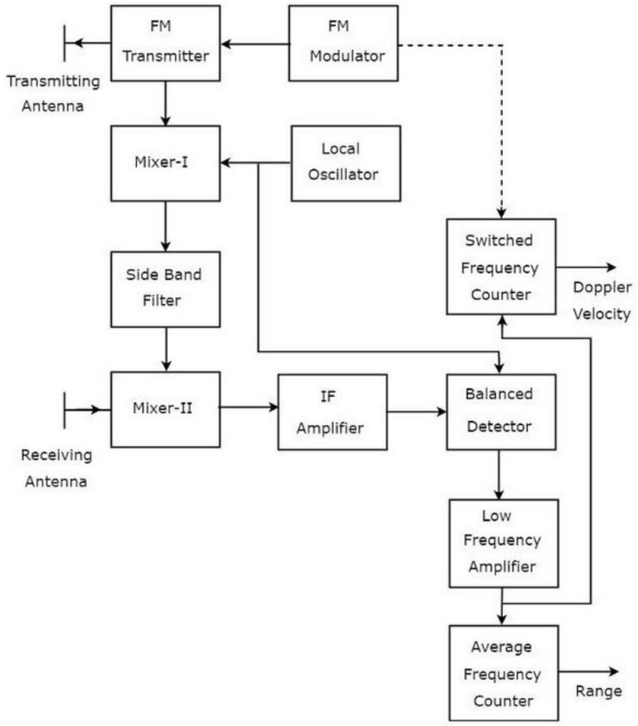

Figure 10. FMCW Radar Block Diagram. Source: https://www.tutorialspoint.com/radar_systems/radar_systems_fmcw_radar.htm [2018]

The figure 10 shows the FMCW radar block diagram. The FM Modulator produces a Frequency Modulated (FM) signal with variable frequency, which is applied to the FM transmitter and is transmitted to the environment through the Antenna. In general, the Local Oscillator is used to produce an RF signal with an Intermediate Frequency. The Mixer-I can produce both sum and difference of the frequencies that are applied to it. In sequence, side Band Filter allows only side band frequencies to pass, i.e., either upper side band frequencies or lower side band frequencies. The side band filter shown in the figure 10 produces only lower side band frequency. Then, Mixer-II can produce both sum and difference of the frequencies that are applied to it. The IF Amplifier amplifies the Intermediate Frequency (IF) signal. Then, the Balanced Detector produces the output signal with the frequency from the applied two input signals. The Low Frequency Amplifier amplifies the output of Balance Detector to the required level. Thus, Switched Frequency Counter is useful to get the value of Doppler velocity and Average Frequency Counter is useful to get the value of Range, finishing the signal flow inside the hardware [10].

The apparent change in frequency or pitch when a sound source moves either toward or away from the listener is called The Doppler-Effect, it also happens when the listener moves either toward or away from the sound source. As mentioned in the beginning of the article, the Austrian physicist Christian Doppler discovered this principle [3].

A radar transmits an electromagnetic wave energy in order to detect the presence of objects and its positions in space observing the echo that is returned. Besides the echo indicates a presence of a target, the echo gives the time elapsed between the transmitted and received pulse, so the distance of the target can be measured. The difference between the signal transmitted and its echo makes the signal separation [3].

When the radar transmitter and receiver are collocated, the Doppler frequency f_d obeys the relationship

$$f_d = \frac{2v_r f_T}{c}$$

Where, f_T represents the transmitted frequency, c is the velocity of propagation and v_r stands for relative (or radial) velocity of target with respect to radar.

In order to segregate the weak echo from the strong leakage signal, the use of independent antennas for transmission and reception is useful although the isolation is not satisfactory. Therefore, an appropriate technique separates the received signal from the transmitted one. This technique uses the relative movement between radar and target recognizing the difference that the Doppler Effect causes in the echo-signal frequency [3].

5. AUTOMOTIVE RADAR

In Brazilian federal highways, 20 deaths and 377 accidents are registered every day. There were 67,427 accidents only in 2019, totalizing 84,383 victims. These accidents resulted in 5,332 deaths in the year. According to CNT (National Transport Confederation), between 2007 and 2019, Brazil had 1.7 million accidents on federal highways, of which 1.2 million had victims and 94 thousand had deaths [11].

The Advanced Driver Assistance Systems (ADAS) brings features of preventive safety applications into the vehicle that can avoid and reduce significantly the statistics above. Besides, most of these accidents and deaths were caused by human errors. Thus, ADAS applications provides safety to the driver by maintaining a safe speed and distance from the vehicle ahead and, therefore, avoiding collisions and injuries to the occupants [6].

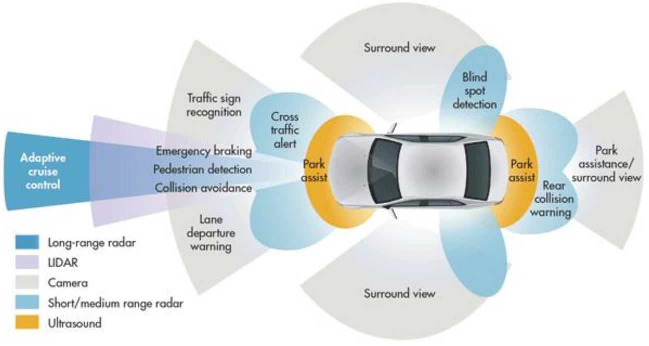

Figure 11. ADAS Features. Source: https://roboticsandautomationnews.com/2016/09/22/advanced-driver-assistance-systems-trump-driverless-cars-by-stealth/7304/ [2016]

The driver assistance system has the objective to bring safety to the driver by managing the vehicle behavior in order to ensure a safer environment for the participants of the traffic, inside and outside the vehicle. Many functionalities as Automatic Emergency Brake (AEB), Adaptive Cruise Control (ACC), Forward Collision Warning (FCW), Blind Spot Detection (BSD) are possible to be developed using only radar services.

To develop this research, a radar with a special software was used, which sends out object data on the CAN bus. In other words, the software collects the information from the objects and send all data organized in blocks through CAN-Bus, so that data can be read, analyzed and manipulated by a specific software.

This radar has a purpose to allow a sensor's evaluation, in order to collect all information needed to apply its functions. Another advantage of using this sensor is that the interface complexity is considerably reduced. The functionalities like ACC (Adaptive Cruise Control) and AEB (Automatic Emergency Brake) can be developed, but this sensor can also be used to develop innovative and brand new functions with the radar.

Normally, a radar has many other functionalities that is organized by modules, this sensor is especially considered as a prototype, only for evaluation purposes and different from others sensors, this one goes from data collect and treatment to object classification.

The radar that has been used in this project is a medium range front radar (MRR Front), which is mounted in one of our demonstration vehicles in order to develop new technologies that can be effective in a near future to help to bring more safety to the Brazilian streets and highways. As mentioned above, this radar has a prototype sensor that must be used only for evaluation purposes.

Thus, following the assembly instructions, the radar was mounted in one of the demonstration vehicles and then a series of procedures, as radar mounting, calibration and alignment, software programming and simulations has taken in order to prepare the radar to operate correctly. After all procedures, the radar installed in the demo vehicle was prepared to start to detect objects. The software used to read and collect CAN data, decode its signals and plot objects on a scatter was Vector CANape 16. This software is useful to do many functionalities related to ADAS applications, such as processing and evaluation of data from previous measurements, calibration and, in this case, to make an object verification for driver assistance systems, using radar, camera or both [14].

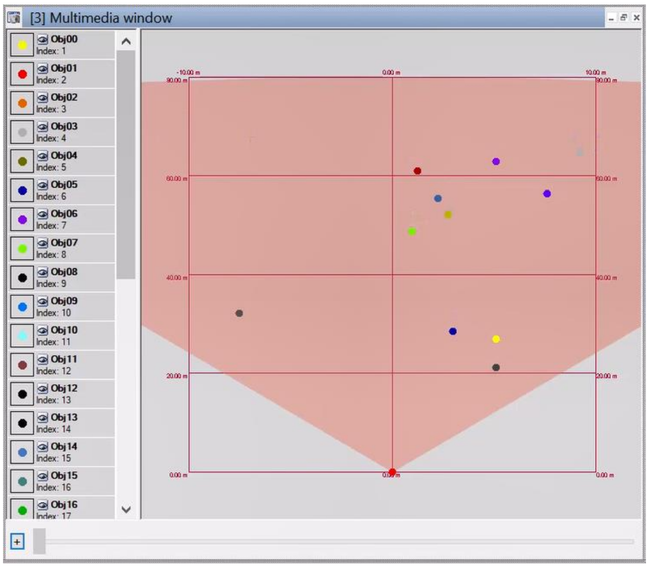

Figure 12. Scatter Plot using Vector CANape 16 [2020]

The plot above shows the objects' positions detected by radar during one of measurements; each point refers to an object. The center of radar is indicated by point zero at the graphics' center, which is the reference point. These objects were identified during measurement and this plot was made in real time during the tests. In addition, it is possible to generate a logging file during measurements, which can be used later with a radar database file that shows all the information collected by the radar. Finally, using a software that can read and interpret this file, we can display all of this data graphically later in the lab.

Furthermore, one feature that is also possible to develop using this radar model is the object classification, an involved process that demands hours of measurements and post processing time. It is possible using one specific signal given by radar that returns what type of object has been detected in real time, such as four or two wheels vehicles, pedestrians or static objects.

6. CONCLUSIONS

This paper contains an overview about radar, including history, concepts (such as Doppler Effect) and applications in daily situations. Therefore, with ADAS advent, the development of this technology has been grown significantly during the last decade, once it increases considerably the safety for all traffic participants, including drivers, passengers, pedestrians, cyclists, among others. In order to keep increasing this safety around the world, studies in this area should continue, bringing new technologies to the market and improving the existing ones. Finally, radar development and its functionalities, like ACC, AEB, BSD and FCW for example, can be also continuously improved, once the study of this technology has been in a constant progress over the years.

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