The Fundamentals of Radar with Applications to Autonomous Vehicles

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Abstract

Radar systems can be extremely useful for applications in autonomous vehicles. This paper seeks to show how radar systems function and how they can apply to improve autonomous vehicles. First, the basics of radar systems are presented to introduce the basic terminology involved with radar. Then, the topic of phased arrays is presented because of their application to autonomous vehicles. The topic of digital signal processing is also discussed because of its importance for all modern radar systems. Finally, examples of radar systems based on the presented knowledge are discussed to illustrate the effectiveness of radar systems in autonomous vehicles.

The Fundamentals of Radar with Applications to Autonomous Vehicles

Introduction

Radar is a technology that is commonly known by most since the technology is critical to many modern systems. Radar is an acronym for radio detection and ranging and is used to sense the location, velocity, and size of objects. Typically, radar is used in military applications for identifying enemy aircraft, missiles, or naval craft. Radar is also used by law enforcement to determine if a vehicle is going over the legal speed limit. While these are some of the most common uses, there are some new exciting uses for radar under development.

Another prevalent topic in the engineering world is the development of autonomous vehicles. Autonomous vehicles have many advantages such as eliminating the error of human drivers, bringing in room for new innovation, and creating new ideas about how we travel. However, one of the major barriers to autonomous vehicles is ensuring that they can properly observe and detect objects in their path and surroundings. These systems must be extremely reliable and fast so that they can react quickly and accurately to any events that happen on roadways and city streets.

Radar can massively assist autonomous vehicles with the task of observing their environment. The goal of this paper is to present some of the base knowledge required to understand radar systems, and some of the techniques and specific aspects of radar that are important to autonomous vehicles systems. Then, some examples of real-world application of radar will be presented to discuss the performance of the technologies in the application of autonomous vehicles.

Overview of Radar Systems

Radar is a complex system that involves many specific subsystems and components that are specific to radar systems in addition to the associated mathematics and terminologies. Understanding these concepts is critical to having a discussion on radar applications. This section seeks to provide a basic understanding of relevant concepts of radar systems so that more advanced radar topics can be presented.

The Basis of Radar Systems

Radar operates on the principle that electromagnetic (EM) waves will reflect off of objects in a predictable way. Radar systems are designed to transmit a certain frequency of EM wave and to use a receiver to listen for what returns. The received data is then processed to determine various aspects of the detected object. Understanding the innerworkings of all radar components would require in depth knowledge of electrical engineering concepts. However, the basic concepts of radar should be established to allow for further discussion.

Anatomy of radar system. Radar systems consist of three main components, the antenna, the transmitter, and the receiver. First, the antenna is the device that is responsible for transmitting the EM waves outwards into free space and is used to detect the returning waves from the object. According to Skolnik (2008), radar antennas are usually designed to transmit EM waves in a narrow beam to concentrate the power and determine the direction of the object; in addition, the antenna usually has a large surface area so that it can detect even the most minute returning signal. The antenna is the component that allows the radar system to interact with the environment around it and must be carefully design for its intended application.

A transmitter generates the EM wave to be sent out and sends it to the antenna. The transmitter usually contains a wave form generator and a power amplifier to ensure that the power of the signal, which can range from milliwatts to megawatts, is proper (Skolnik, 2008). The frequency of the generated wave can vary from application to application. According to Richards, Scheer, and Holm (2010), “Radars operate in the range of 3 MHz to 300 GHz, though the large majority operate between about 300 MHz and 35 GHz” (p. 7). The frequency chosen for a given system depends heavily on the application, various required design parameters, and any governmental regulation that exists in the area.

The receiver is much more complicated than the transmitter of a radar system. Receivers include all of the components that are required for detecting the echo of a signal, which can be extremely small. In a typical radar system, there is a low noise amplifier (LNA), a local oscillator, and a mixer at the beginning of the receiver immediately after the antenna (Skolnik, 2008; Richards et al., 2010). These components amplify the received signal and the local oscillator, and a mixer moves the signal down to an intermediate frequency (IF) the system can more easily analyze. Next in the receiver is the IF filter, the detector, and then the signal processor (Richards et al., 2010). These components turn the received signal into data that can be processed into useful information. An example of a general receiver structure can be seen in Figure 1.

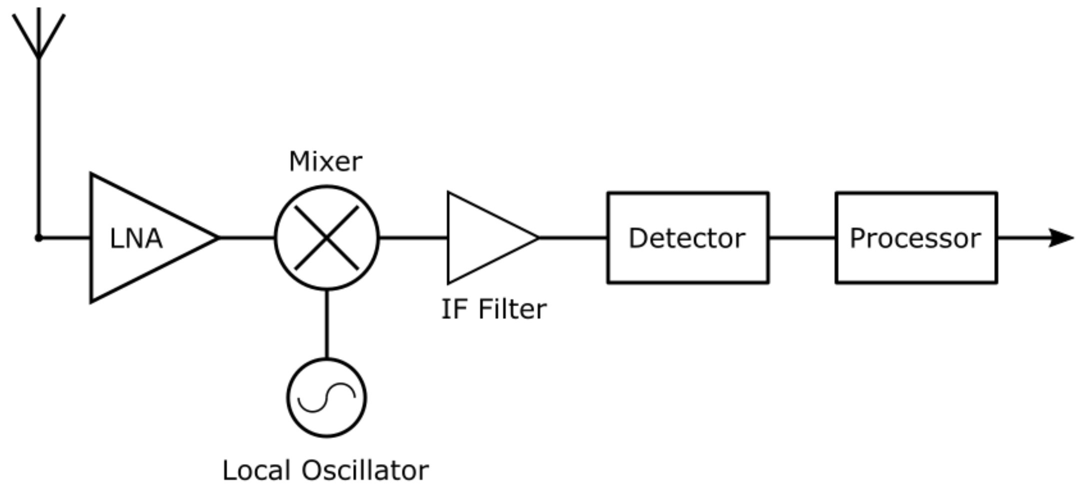

Figure 1. An example of a basic radar receiver structure.

Radar systems can vary as to how the receiver, transmitter, and antenna are oriented. In any radar system, the receiver needs proper isolation from the powerful transmitters. Components in the receiver are very sensitive, and a high-power transmitter could destroy those components if it is not properly isolated. The device that performs this task is called a duplexer or T/R Device, which is a kind of switch or circulator when the antenna is mechanically rotating (Skolnik, 2008; Richards et al., 2010). In addition, systems can either have one antenna which is shared between the transmitter and the receiver or the transmitter and receiver have their own dedicated antenna. The configuration a system uses depends on the application.

Important radar measurements. Radar units can fulfil the needs of many different applications, but regardless, they all perform the same measurements. Depending on the radar's application, some measurements may be more important than others. Therefore, radars are typically designed to maximize their ability to perform certain measurements. Regardless, measurements provide the essential information about the environment of interest.

Firstly, radar systems need to measure the position of an object. The parameters that a radar system is looking for are the azimuth and elevation angle, and the range of the object (Richards et al., 2010). These parameters combined will give the target's position in three-dimensional space using a spherical coordinates system. The spherical coordinate system is key to radar systems and an example of a spherical coordinate system is shown in Figure 2. The position of an object in space can be determined from the direction the radar is pointing and some properties of the EM wave.

Range is determined by measuring the amount of time it takes for a wave to be transmitted and then received by the radar antenna (Skolnik, 2008). This is a simple calculation using time and velocity. Since we know that electromagnetic waves propagate at the speed of light, we only need to know the travel time of the wave to determine the distance to an object. However, one aspect of electromagnetism is that waves may propagate at a slightly different speeds through different materials. According to Skolnik (2008), one of the limiting factors of radar accuracy is the knowledge of the speed of propagation in certain environments; however, this should only be a problem at long ranges. Therefore, accurate time measurements and knowledge of the environment are required to create accurate range measurements.

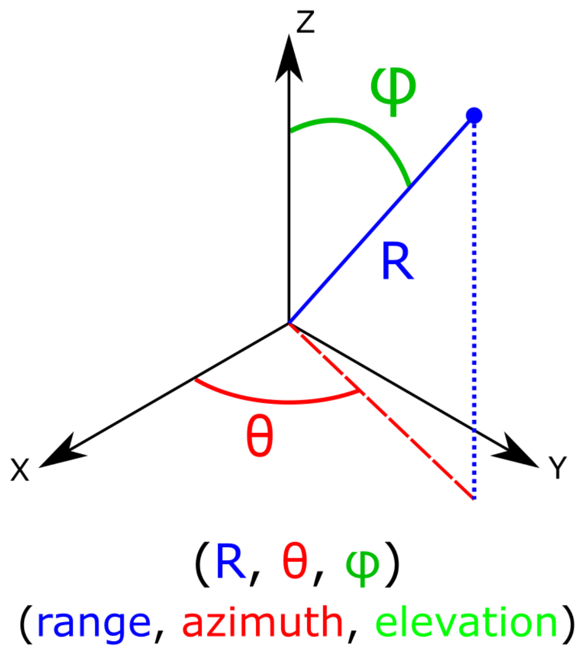

Figure 2. An example of a polar coordinate system. The symbols used and their placement can vary between sources.

Another important radar measurement is the velocity of a detected object, which describes if a detected object is moving or not. This is done by measuring the Doppler shift of the returning wave (Richard et al., 2010). The Doppler shift occurs when an object moves and emits a wave. The progression of the object through space compresses or stretches the wave. The Doppler shift also occurs when an EM waves reflect off a moving object. Therefore, by measuring the Doppler shift of the returning wave, one can determine the velocity of the detected object.

The polarization for the returning wave can also provide useful information about the target. According to Richards et al. (2010), the size and shape of the target will change how certain parts of the wave reflect of the object, and therefore useful information about the target shape can be deduced from the polarization of the wave. Hence, the rough geometric shape of the object can be determined by the polarization of the returning wave. All the previously mentioned measurements are important to radar systems. These combined measurements can give an accurate description of position, velocity, and the general shape of the object. How much these properties matter to the radar systems varies on the specific application for that system.

Radar functions. Radars perform a few core functions that allow them to fulfill their objectives. According to Richards et al. (2010), these functions are search and detect, tracking, and imaging. Search and detect is the function that comes to mind when one considers radar. Radar systems search a given volume of space to detect any objects that are present in said volume. Tracking is a sort of extension of search and detect. When a radar system detects an object in the search space, it can then estimate its velocity and trajectory. This allows the radar system to create a track of the object which shows how the object is moving (Richards et al., 2010). These are the two common functions of radar that allow for radar systems to perform extremely complex tasks. The third function of radar is imaging. Imaging radar's primary function is to create a still image of an environment and potentially provide target identification tasks (Richards et al., 2010). Imaging radar is versatile and can be used for many applications.

The Radar Range Equation

There are many complex equations that apply to radar but there is one equation that relates to all of them and is critical to their design and operation. This equation is called the radar range equation and relates variables about the antenna, the emitted wave, and the environment. It can be used to derive many variables such as the radar cross section of the object, the range of the object, and important information about the noise in the system. There are more equations, but they are much more specific and would be too lengthy to cover in the scope of this paper.

The simple form of the equation. There are several forms of the radar range equation but some are extremely complex. Therefore, the simplest form is explored to provide basic understanding. Skolnik (2008) has stated that the simplest form of the radar range equation is as follows:

$$P_r = \frac{P_t G_t}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_e \qquad (1)$$

The variables P_r and P_t represent receiving and transmitting power respectively. G_t is the gain of the antenna. A_e represents the effective area being scanned, and R is the distance from the object. All of these variables, except R, should be known; therefore, one can use this equation to find R.

One important term not mentioned thus far is σ. This variable represents the radar cross section and defines how well an object reflects EM waves. Richards et al. (2010) states, “the radar cross section of a target is determined by the physical size of the target, the shape of the target, and the materials from which the target is made, particularly the outer surface” (p. 62). To continue, the important aspect of this equation is that it relates the power of the transmitted wave, the radar cross section, and the scanned area to the returning power of the signal. This equation allows the system to extract information from the power of the returning wave, and it is used as a basis for all radar design.

Negative contributions to performance. Unfortunately, radars cannot perform ideally in the real world. There are many forms of interference that come from the environment that disrupt ideal performance. Richards et al. (2010) splits them into the categories of noise and clutter. Noise is present everywhere in one form or another and affects all radar systems. The most common form of noise is thermal noise. Thermal noise comes from the environment and originates from EM waves emitted by the vibrations of atoms (Richards et al., 2010). Noise is measured by a parameter called signal-to-noise ratio (SNR) which expresses how the strength of the noise relates to the strength of the signal. The largest concern with respect to noise is that it is random, and if not properly accounted for, noise might randomly reach a level that causes a false detection (Richards et al., 2010). Noise is always present, and many techniques have been developed to minimize it.

The other form of interference is clutter. Clutter comes from other objects in the range of the radar system that are not targets; therefore, it is a more complex signal than random noise. Richards et al. (2010) describes that the two kinds of clutter are surface and volumetric. Surface clutter can come from surfaces such as the ground, bodies of water, and weather, such as rain or snow. Volumetric clutter is essentially atmospheric clutter where a volume of atmosphere reflects a measurable wave. Clutter provides interference because it reflects waves that the system is not interested in, and these waves need to be separated from the important reflected waves. Clutter is quantified by signal-to-clutter ratio (SCR) similar to SNR.

Summary

Radars can detect, track, and image a given environment. These functions are all performed through the same universal measurements in all radar systems. All of this is rooted in the math and science of how electromagnetic waves interact with physical objects, and it is the foundation of all radar technologies relevant to autonomous vehicles.

Overview of Phased Arrays

This section focuses on the more complex subject of phased arrays in radar systems because it is extremely useful for the application of autonomous vehicles. Many radar systems rely on mechanically rotating antennas to direct the radar beam. This can present problems because you have to be concerned about the mechanical failure of the antenna which would cripple the radar system. Also, physically rotating radar antennas can consume significant power if the dish is significantly large. Therefore, there are major disadvantages of mechanically rotating antennas.

Phased arrays are complex antenna arrays that electrically steer the radar beam so that the antenna does not need to rotate mechanically. Antenna arrays are large groups of antennas all designed to work together to perform a task. In phased arrays, they are manipulated in such a way that the EM waves propagate in a specific direction. Therefore, they are referred to as being steered electronically, because the steering is done by careful manipulation of electronic circuits. Phased arrays avoid the complications that are brought up by mechanical arrays while performing the same functionality. However, there are some disadvantages, too (Richards et al., 2010; Melvin & Scheer, 2014). Phased arrays are extremely useful and are relevant to the autonomous vehicles.

Basic Principle of Phased Arrays

Phased arrays have many different configurations but rely on the same operating principle. This principle is described by Hubgret J. Visser (2005):

> The non-zero distance between the isotropic radiators [antennas that emit radiation equally in all directions] - that may be thought of as making up the antenna - cause phase differences in the fields radiated into the different directions. These phase differences will cause constructive interference in some directions and destructive interference in other directions. (p. 83)

This means that antennas any distance apart from each other can emit radiation that can add to or subtract from radiation emitted from other antennas. This constructive and deconstructive interference is what allows an engineer to carefully design phased array antennas to point their radiation in a specific direction. This is done by changing the phases of signals that each antenna element transmits. The practice of designing specific radiation patterns is typically referred to as beam forming.

Active versus Passive Arrays

All phased array antennas consist of a series of individual antennas arranged in a specific geometric pattern. However, phased arrays fall into two categories. These categories are active and passive arrays. Parker and Zimmermann (2002a) describe the difference between these two arrays:

> Passive arrays use a central transmitter and receiver, but have phase-shift capability at each radiating element or subarray. In active arrays, the high-power generation for transmit and low-noise amplification on receive are distributed, as is the phase control at each radiating element. (p. 678)

This shows how passive arrays only have control of the phase of each antenna while active arrays have dedicated transmit and receive modules (including amplifiers) at each antenna.

Both passive arrays and active arrays have their advantages and disadvantages. Passive arrays are less expensive because they have the least number of components since there is only one central receive and transmit unit, but they have no amplitude control at each element which means that they have to be carefully designed to avoid significant amplitude loss in the antenna (Parker & Zimmerman, 2002a). Active arrays have the advantage of having much more precise control at each antenna in terms of amplitude and phase control; however, active arrays are significantly more costly than any passive array because each antenna has its own transmit and receive units (Parker & Zimmerman, 2002a). These are the main advantages of passive and active arrays as well as some of their potential issues.

Layout of Arrays

Phased arrays can have two main layouts. Each has similar components but differs in how they are physically arranged. However, there are some terms that apply to both layouts of phased arrays that need to be discussed. Firstly, antennas in a phased array are commonly referred to as elements of the array. Radiation beam and radiation patterns are another regularly occurring term used when discussing phased arrays. In this context, radiation refers to the EM waves that are emitted by the system and the radiation pattern is how those waves are spread out over a space. All phased arrays have their own distinct radiation patterns.

Linear arrays. The first layout of an array is a linear array. Linear arrays are the ones whose array elements are arranged in a straight line as shown in Figure 3. These are the simplest form of antenna array since the arrays are laid out in one dimension. When arrays are activated, they will produce a unique beam pattern that describes where the power of the transmitted wave is concentrated. The beam pattern is affected by variables such as the distance between the array elements, the number of array elements, and the electrical current in each element (Parker and Zimmerman, 2002a). Engineers will strategically change these parameters to create the desired beam pattern.

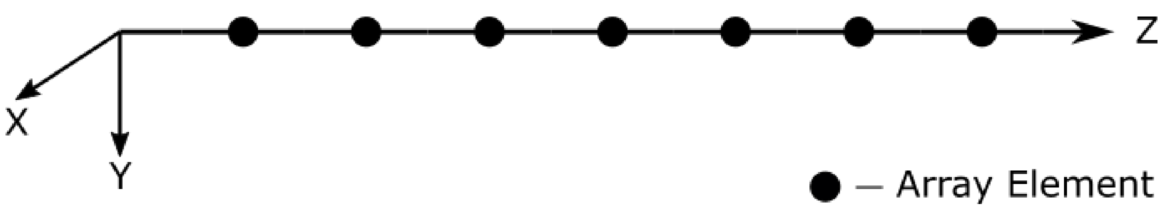

Figure 3. Graphical representation of a linear phased array.

Planar Arrays. Planar arrays perform the same functions as linear arrays but consist of antenna elements laid out on a two-dimensional plane instead of a straight line as shown in Figure 4. Parker and Zimmerman (2002a) mention that planar arrays can be arranged in triangular, rectangular, or circular patterns depending on the desired beam pattern. It should be noted that most equations concerning planar arrays use a spherical coordinate system where the positive *z*-axis is normal to the planar array (Hansen, 2007). Planar arrays allow for the system to scan in both the azimuthal and elevation directions, allowing for the system to electrically scan 3D-space without the antenna array physically moving.

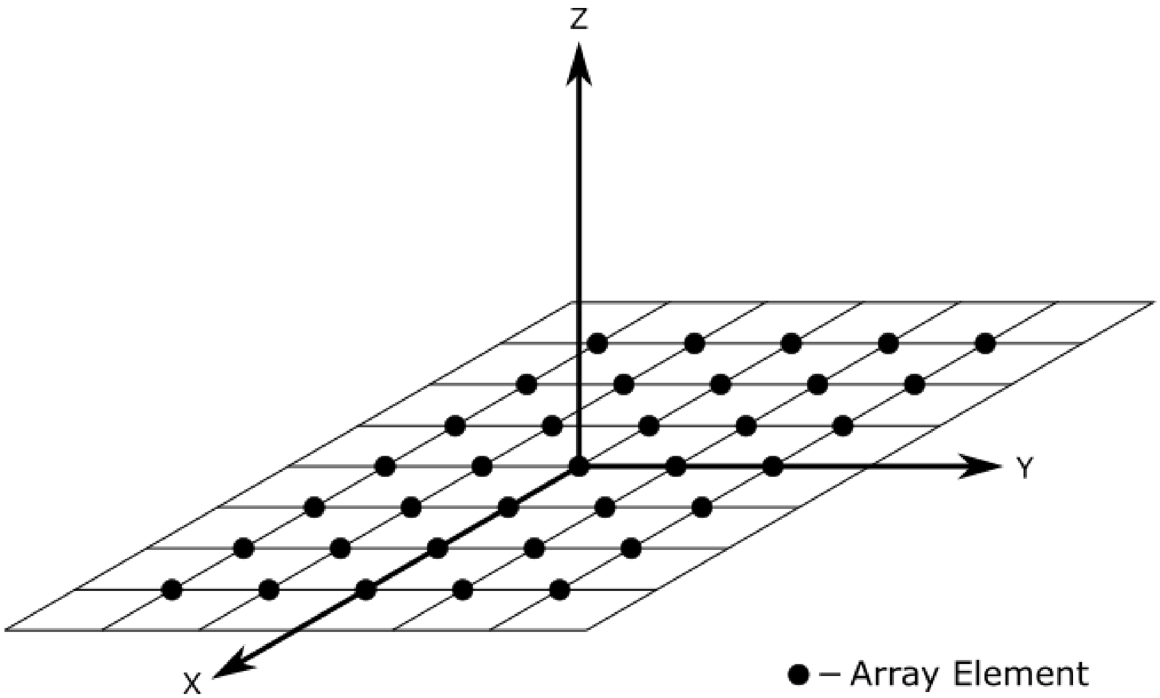

Figure 4. Graphical representation of planar phased array. The *z*-axis is almost always orthogonal to the plane that the arrays are in.

Planar arrays are more difficult to design since they are dealing with three-dimensional space and two dimensions of array elements. However, Parker and Zimmerman (2002a) state that many of the core concepts of beam forming for linear arrays can be applied to planar arrays. While the concepts are the same, Hansen (2007) covers some of the actual mathematics of planar array beam forming, and the mathematics are much more complicated for planar arrays. However, the payoff for the increased complexity is the increased functionality of the array.

Why Phased Arrays

Phased arrays are useful for creating three-dimensional radar systems. Some radar systems are only able to provide a range and a detection angle which only gives a two-dimensional perception. However, three-dimensional radar systems can provide a three-dimensional position of a detected object. Melvin and Scheer (2014) discuss how the military is transitioning to three-dimensional systems so they can obtain three-dimensional positions of targets, and they are using phased arrays due to their ability to implement various beam scanning techniques. Phased arrays can be used to effectively implement three-dimensional radar systems due to the directed beams that they are able to create and steer electrically.

Phased arrays also have some physical characteristics that make it useful for cars. Firstly, phased arrays require no moving mechanical parts. A large mechanically rotating antenna would be impractical for any vehicle because of the massive amount of space that one would use. Phased arrays allow for directional radar systems with much more compact and non-mechanical antennas. Phased arrays are also significantly faster than mechanically steered arrays. Skolnik (2008) states, “prior radars took seconds to steer to a new location, phased arrays take microseconds” (p. 13.1). This significant speed advantage could be extremely useful in autonomous vehicles. Also, phased arrays are low profile compared to other radar systems. Richards et al. (2010) describes how the low profile of phased array systems makes it quite suitable for stealth aircraft applications. This low-profile nature is quite useful for vehicles as well.

Overall, phased arrays have quite a few advantages over normal antenna systems, but still have their disadvantages. Phased arrays do not need to move mechanically which means they can be significantly smaller, and they cannot fail mechanically. They can be electrically steered which can sweep an area much faster than any mechanical radar can. However, phased arrays are costly. They involve many more components and use precise electronics. There is much more engineering and design work that must go into designing a phased array than typical radar systems.

Relevant Digital Signal Processing Techniques

All radar systems must turn the data it receives into useful information, and most modern radar systems use digital signal processing to extract information from the returning EM waves. Digital signal processing (DSP) uses a digital system to process signals instead of using analog components. This can be done with microcontrollers, field programming gate arrays, full computers, or dedicated digital signal processing units. The field of DSP is vast and is a field of its own outside of radars.

Digital signal processing brings a lot of potential to the table while also having its own draw backs. For example, more complex systems can be implemented using digital signal processing than using analog components. Complex systems implemented using analog hardware could require hundreds or thousands of physical components to complete. A digital system consists of an analog-to-digital converter (ADC), a processor, and some code. One of the disadvantages of DSP is that it introduces some delay into the system. This occurs because the signal is processed in synchronization with a clock signal after it goes through an ADC. The clock is typically the bottleneck of the system in terms of the system's speed. Therefore, they must be designed carefully to avoid introducing too much delay. DSP plays an important role in radar and the relevant processes involved will be covered.

Digital Signal Processing Basics

All digital signal processing techniques are based on the same fundamentals. There are many aspects to DSP due to the vastness of the field, but some of the DSP basics should be covered. These basics form the foundation of many of the ideas in DSP while also showing some of the advantages and disadvantages of DSP as a whole. Therefore, a few of the basic fundamental principles of DSP will be discussed.

Sampling and quantization. The first step of DSP is sampling and quantization. The process of sampling and quantization is done with an analog-to-digital converter (ADC), which converts analog, continuous signals into a discrete signal. Tuzlokov (2013) describes the sampling process as taking a piece of the signal instantaneously and periodically. Quantization is the accompanying process to sampling. Quantization is the process of taking an analog amplitude value and assigning a discrete binary value (Tuzlokov, 2013). This shows one of the disadvantages of DSP. When a signal is quantized, it loses some information about its amplitude. The binary numbers that can be assigned to a signal are limited by the bits of the ADC, and therefore a higher bit ADC can help mitigate the effects of quantization. Sampling and quantization work together to convert analog signals into digital samples that can be processed by a digital system.

One of the important parameters for sampling a signal is the sampling frequency. The sampling frequency has a significant effect on how the signal is preserved. Choosing a sampling frequency that is too low will result in an improper signal. A theory dealing with the question on how fast you have to take samples is called the Nyquist sampling theorem. The Nyquist sampling theorem states the sampling frequency should be greater than twice the maximum frequency, or, in other words, greater than the bandwidth of the signal (Richard et al., 2010). This frequency is extremely important and needs to be accounted for when designing any DSP system.

Fourier analysis. One of the major mathematical principles that engineering relies on is the Fourier transform. The Fourier transform takes a function of time and transforms it into a function of frequency. Converting a function into the frequency domain allows for more information about the signal to be obtained. Using the Fourier transform to look at the frequency spectrum of a signal is commonly referred to as Fourier Analysis. Fourier Analysis is one of the cornerstones of DSP and electrical engineering itself due to its invaluable utility.

The Fourier transform is defined to be continuous in time and frequency; therefore, it cannot be directly computed for a digital signal because a digital system is discrete. A digital system would need to have infinitely long variables and infinite computations to precisely perform the Fourier transform. Thus, the Fourier transform must be discretized. Richards et al. (2010) detail the two major algorithms that are used: the discrete Fourier transform (DFT) and the fast Fourier transform (FFT). These two algorithms are the ones that are used to perform the Fourier transform in a purely discrete fashion. The FFT is simply a more time efficient and faster version of the DFT (Wang, 2002). FFT is commonly used in almost all computational tasks because it is more efficient and therefore requires significantly less processing power.

Digital filtering. The third basic aspect of DSP is digital filtering techniques. Filtering is a topic that is critical to any system dealing with electrical signals. Filters are designed to remove electrical signals of frequencies that are not of interest to the system so that the signal of interest can be properly analyzed without the interference. Filtering has traditionally been done with carefully designed hardware utilizing capacitors, resistors, operational amplifiers, and inductors. These filters can become extremely complex to design and would require many components to have desirable filtering characteristics. However, digital filtering can achieve significantly better filter designs with the compromise of introducing a delay into the systems. A carefully designed digital filter can achieve much more than an analog filter design with a negligible delay in the signal.

All filters are characterized by the impulse response $h(t)$ in the time domain or the transfer function $H(s)$ in the frequency domain. These terms are used frequently when characterizing and describing filter designs. According to Richards et al. (2010) there are two kinds of filters, finite impulse response (FIR) filters and infinite impulse response (IIR) filters. All digital filters fall into one of these two categories. IIR filters are also sometimes referred to as recursive filters because they use feedback while FIR filters do not use any feedback (Richard et al., 2010).

FIR filters are characterized by their finite impulse response. Richards et al. (2010) state that the finite nature of FIR filters means that they are inherently stable. Another useful characteristic of FIR filters is that they have a linear phase response, and therefore all information about the phase of the signal is preserved (Richards et al., 2010). This is extremely useful for radar systems since the phase of the returning signal can be used to determine much about its properties.

The other kind of digital filters are IIR filters. They are characterized by having infinite impulse responses due to the fact they attempt to mimic analog filter designs and transfer functions directly. IIR filters contrast to FIR filters because they are not inherently stable and they do not have a linear phase response, but they have a significantly smaller order than FIR filters to achieve the same performance (Richards et al., 2010). Filter order is essentially the number of coefficients that are required to implement the filter. Therefore, a filter with a lower order is much easier to implement than a filter of higher order. The largest disadvantage of IIR filters is that they are not inherently stable. Much more care must be taken when designing an IIR filter to ensure that it is stable and does not become unstable when it is implemented.

Detection Methods

A critical function of radar is to determine when something has been detected within its search area. The simplest detection method is to set a simple threshold detector that detects when the received signal’s amplitude goes over a set value. However, this simple method is not used in any modern radar systems. Skolnik (2008) states, “In the original work on detectors, the environment was assumed known and homogenous, so that fixed thresholds could be used. However, realistic radar environment … will cause an exorbitant number of false alarms" (p. 7.2). A fixed threshold detection method can work but will produce many false alarms. These errors occur when the amplitude of any noise or interference crosses the fixed threshold. Therefore, adaptive thresholds are used. An adaptive threshold adjusts itself based on the noise and interference in the environment to hold a constant false alarm rate (Richard et al., 2010). This is extremely useful for processing data so the user can know the probability that a detection is false and not an actual object.

Detection theory is based heavily on statistics since a detector's key parameters deal with the probability of certain events occurring. The major parameters related to detection that are of interest to the user are the probability of detection and the probability of false alarms (Richard et al., 2010). Both terms not only characterize the detector but also characterize the entire radar system. The statistical equation that is used to determine whether a detection has occurred is called the Neyman-Pearson criterion which maximizes the probability of detection for a chosen probability of false alarms (Skolnik, 2008) The probability of false alarms must be chosen first, and then a probability of detection can be found after that. The probability of false alarms must be chosen wisely and within a reasonable tolerance for the application. The statistical analysis of detectors is lengthy and is a subject in its own right.

One of the important aspects of detection is SNR. SNR has an effect on the probability of detection and the probability of false alarms. Richards et al. (2010) describe how increasing the SNR while locking the probability of false alarms increase the probability of detection. Therefore, increasing the SNR can be useful when nothing else can be done to increase the probability of detection. This is done with a matched filter. Matched filters have an impulse response that is matched to the expected signal, hence maximizing SNR; however, matched filters are extremely hard to implement with analog components (Tuzlokov, 2013). Hence, they become much more realizable with digital processing systems.

There are many methods for implementing detectors and their systems. Skolnik (2008) discusses some practical detectors called moving window, binary integrator, and batch processors. These detectors represent some of the more common ways the detectors are implemented. The moving window detector is simply the "running sum of *n* pulses in each range cell" (Skolnik, 2008, p. 7.4). This method then uses these sums to detect whether an object is in a certain range cell or not. A range cell refers to how a space within the range of a radar unit is discretized and an area of space is treated as a cell, which allows for it to be easily stored in an array of values.

Binary integrators are one of the common implementations of detector units. Skolnik (2008) describes binary integrators as working in the following manner:

> The input samples are quantized to 0 or 1, depending on whether or not they are less than a threshold T_1. The last N zeros and ones are summed (with a moving window) and compared with a second threshold $T_2 = M$. (p. 7.7)

Binary integrators are also known as M-out-of-N detectors due to the M and N terms that are used during its operation. Binary integrators are easy to implement and are tolerant to sudden interference spikes but suffer greater errors due to the quantization of the data early in the detector (Skolnik, 2008). Overall, binary integrators are a simple method and can be used to simplify a design whenever the errors are acceptable.

Detection theory is extremely important for radar systems. Many detectors' aspects are deeply rooted in statistical theory applied to signal analysis. There are many aspects of detectors that could not be discussed in the scope of this section, but some of the essentials have been provided. Regardless, many detection techniques are performed using digital techniques due to the advantageous that DSP techniques provide.

Doppler Processing

Doppler processing is a reference to processing data to measure the doppler effect that is occurring. As mentioned earlier in this paper, the Doppler effect is when a wave's frequency is increased or decreased depending on the velocity of the object the wave interacts with. This information is extremely useful in some cases. The main uses for doppler processing are moving target indication or finding the radial velocity of an object. (Richards et al., 2010). Doppler processing is typically done digitally once the data has been collected by an ADC, and therefore relies heavily on DSP techniques.

The doppler shift is typically found by performing spectral analysis. This is performed using the Fourier transform mentioned previously to observe the frequency spectrum. The Doppler shift will then represent itself as a shift in the spectrum of the returning wave. An example of this can be seen in Figure 5. Waves that are returning from a moving object will have a shifted frequency spectrum compared to the frequency spectrum returning from stationary objects (Richards et al, 2010). This frequency is referred to as the doppler frequency and can be used to find the radial velocity of an object.

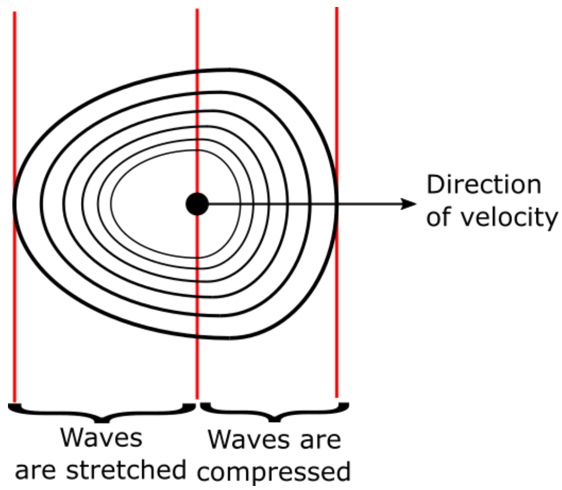

Figure 5. An object moving through space that is emitting waves will compress the waves in front of it and will stretch the waves behind it.

Doppler processing is a relatively straight forward process. By analyzing the frequency of the returning signal using the Fourier transform, any shift in the frequency spectrum can be measured. That simple shift can then be evaluated and used to generate important information. In digital systems, the Fourier transform would be done with a DFT or FFT algorithm on the data retrieved from the ADC. Overall, Doppler processing is a simple process performed by DSP and has useful applications in radar systems.

Algorithms

Any computational system has algorithms to perform tasks. An algorithm is typically a general pattern, rule set, or procedure for a computer to solve a problem. Radars use many digital algorithms to perform tasks such as target detection and target tracking. There are far too many algorithms to talk about each one in detail, therefore this section will focus on range tracking algorithms to provide an example of a basic engineering algorithm.

A radar can receive a lot of data about a target, and tracking algorithms use that data to provide a continuous track of an object of interest. For example, a target range tracking algorithm continuously measures the time delay between the transmitted signal and the echo (Tuzlokov, 2013). This range tracking algorithm allows for a track to be created of an object's range from the radar. Having this information along with angle information can provide an exact path of an object moving through the space.

Despite the previous description, range tracking is slightly more complicated than simply transmitting a pulse and waiting for a response. If an object is outside of the beam of the radar, then the object could be undetected for a significant period of time. Therefore, once a target is acquired, a tracking algorithm will lock onto the target, and try to contentiously point at the target and determine its range (Tuzlokov, 2013). Being able to track a target accurately is a complex task that requires mathematically rigorous algorithms that are usually implemented in complex computer code. Tuzlokov (2013) breaks down a range tracking algorithm in the following way: a radar accepts or rejects a detection, associates the detection with an existing track, updates the existing track, gives a new track to any detections not associated with a track, and then uses all tracks to determine how it should be scheduled and controlled. All steps involve a significant amount of DSP and mathematics.

Applications to Autonomous Vehicles

Autonomous vehicles are an up and coming technology that has massive implications for society in terms of the economy and safety. Autonomous vehicles will remove the human factor from transportation which will lead to improved safety on the roads and a massive reduction in fatal accidents. There are also implications for the economy due to the fact that autonomous vehicles will reduce transportation jobs as they are replaced by machines, but also fewer people will be spending money on repairs from accidents. The implications of autonomous vehicles are wide reaching and will change many aspects of society's infrastructure.

Autonomous vehicles do come with their innovative challenges and drawbacks that make them not quite ready to be deployed. One of these challenges is using sensors to detect the environment around the car. Patole, Torlak, Wang, and Ali (2017) describe that many technologies are used, such as light detection and ranging (LiDAR), ultrasonic, sensors, and radar. Radar does have some major advantages over the other technologies. For example, Ju, Jin, and Lee (2014) state, "[Radar systems] are virtually unaffected by hard environmental conditions such as poor weather and/or light quality" (p. 1). Hence, radar units are a massive area of interest when it comes to autonomous vehicles.

There are many kinds of radars that are used in autonomous vehicles, but most share the same frequencies. Dudek, Kissinger, Weigel, and Fischer (2011a) state, "As a result of world-wide standardization efforts future automotive radar will operate at 76 GHz to 81 GHz band where the essential bandwidth for short as well as long range radar (LRR) systems is allocated." These operating frequencies are one of the most common to be represented in literature. However, Ding et al. (2015) discuss creating an automotive radar system in the 24 GHz to 24.25 GHz and the 24.25 GHz to 25.65 GHz ranges. Either frequency range is used depending on the desired characteristics of the radar system.

There are some important requirements for radar systems applied to autonomous vehicles. There is a considerable amount of safety requirements that must be considered when dealing with autonomous vehicles. As a result, Ding et al. (2015) define the necessary requirements as “highly reliable hazard detection capability, a very low false alarm rate, and rapid target acquisition and characterization” (p. 265). All of these are necessary for radar to be truly useful for autonomous vehicles. If these characteristics are not properly implemented in a design, then there could be disastrous consequences for the systems, any users of the system, and potentially innocent bystanders. All radar systems should strive to ensure that these qualifications are met.

Applications of Phased Array

As stated earlier, phased arrays can have useful applications in autonomous vehicles. Phased arrays have a lot of desirable characteristics that make them attractive for automotive use. Their ability to create precise beam patterns and steer the beams without the need for mechanical parts is one of those characteristics. Dudek et al. (2011a) state that phased arrays provide increased accuracy, angle resolution, and reliable target detection. These traits are “essential for the next generation of automotive radar sensors” (Dudek el al., 2011a, p. 1478). Phased arrays have many benefits that make them suitable for applications in autonomous vehicles.

Phased arrays also have the advantage of being able to form many different beam patterns. Dudek et al. (2011a) describe, “the automotive area the beam has to be steered in a range of some degrees depending on the specific application is built for, either as short or as long-range radar” (p. 1479). Phased arrays have a lot of diversity since they can be designed in so many ways. This allows phased arrays to fill many roles as adding a few antenna elements can drastically change beam pattern. Ku, Inac, Chang, and Rebeiz (2013) describe how having a sixteen to thirty-two element array can create a narrow beam pattern which is useful for some automotive radar functions. The flexibility of phased arrays can provide extreme versatility to automotive radar units.

The performance of phased array radar systems is quite excellent when taken into consideration. Schmalenberg, Lee, and Shiozaki (2013) discuss the results of their phased array systems, which can distinguish between a pedestrian and a stopped vehicle behind them as two separate objects and detect both of their distances and sizes. These results are quite amazing since the pedestrian is standing in front of the stopped vehicle. Other systems, such as LiDAR or ultrasonic would have some difficulties seeing behind the pedestrian and fail to identify that there was a stopped car. The ability of the phased array antenna to distinguish the range of two overlapping objects in its field of view is extraordinary.

Also, phased arrays can be used to create tracks of targets. Schmalenberg et al. (2013) describe how another part of their test was to test the tracking abilities of the radar system. Schmalenberg et al. (2013) set up a testing circumstance where pedestrians would start behind a radar absorbing wall, and then walk across the test area, and then stop behind another absorbing wall. The results of the test were that the radar system was able to track all targets despite the fact that there were times that the pedestrians were out of site of the radar. The radar system's tracking of multiple targets helps fulfill some of the necessary requirements of radar systems to operate in autonomous vehicles.

An interesting detail that appears when reviewing the literature on the subject of phased arrays is the fabrication of radar chips and the semiconductor that is used. Schmalenberg et al. (2013) discuss making a singular printed circuit board that has a sixteen by sixteen element array and a SiGe based radio frequency integrated circuit (RFIC). One of the important details here is the SiGe based integrated circuit. Ku et al. (2013) state that "SiGe is the only silicon technology which is currently approved for automotive radars" (p. 371). This is likely due to the high frequencies involved with radar systems and SiGe likely has desirable characteristics in that frequency range since it is the only approved silicon for such applications.

Another interesting detail is the simulation of the radar system to test performance. A common method that is used in much of the literature is three-dimensional ray tracing. Dudek, Kissinger, Weigel, and Fischer (2011b) describe using a three-dimensional ray tracing unit to test their proposed design for a phased array radar unit in a simulated real-world scenario of navigation around a parked vehicle. Ray tracing is a computer technology typically used to calculate rays of light to then generate graphical images, but here it is being used to calculate radar waves being emitted, reflecting off surfaces, and then returning to the radar unit. It is an interesting and complicated subject matter but is intriguing to see it used to accurately simulate radar systems without having to be physically deployed.

Frequency Modulated Continuous Wave Radar

One of the common topics that arises when talking about radar systems applied to autonomous vehicles is frequency modulated continuous wave radar (FMCW). Continuous wave alludes to how the radar system is continuously emitting an EM wave. The reason that the wave is frequency modulated is that for a continuous wave system to be able to detect range, there must be some way to encode time into the wave, and in this case, it is the frequency of the wave (Melvin & Scheer, 2014). Essentially a FMCW system modulates a continuous wave with frequency so that when the waves return to the receiver, the time it was emitted can be known, and therefore the range as well.

One of the common nomenclatures used to describe FMCW systems, that should be discussed, is the waveform of the system. The waveform is a plot of the frequency being used by the radar system with respect to time. Commonly, FMCW systems use a variety of linear wave forms such as a sawtooth waveform or a triangle waveform, and such a system is referred to as linear frequency modulation (Melvin & Scheer, 2014). These waveforms describe how the radar system will change its frequency with respect to time. The transmission wave can then also be directly compared to the received waveform to reveal important information such as the doppler shift of the return wave (Melvin & Scheer, 2014). The waveform of a FMCW is incredibly important and is used to describe how the system changes its frequency with respect to time.

Application of FMCW to Autonomous Vehicles

FMCW radar systems have been widely used in the automotive industry for some time, so plenty of literature has been produced on the subject. However, recent research presents some interesting findings as FMCW is applied to autonomous vehicles. The topic also intersects with phased array and other radar topics as well, because FMCW can be performed on most systems since it is method of transmitting a signal and is not tied to a specific system architecture.

As stated earlier, radar systems for autonomous vehicles must have a low false alarm rate or there could be potentially disastrous consequences for those involved. One paper seeks to address the concerns of false alarms by using a unique waveform for FMCW systems. Fan, Xiang, An, and Bu (2013) created a unique waveform for FMCW radar and an algorithm that processed the returning waves. The research resulted in a FMCW system that produced zero false detections. The wave form used is a ramp function that will ramp up to a frequency, then hold that frequency for a short period, then ramp back down and repeat; however, when the frequency is constant, the waveform is modulated with a PN code so those waves can be distinguished in time (Fan et al., 2013). This unique waveform for FMCW radar is quite innovative and can definitely be useful for autonomous vehicles.

Another paper seeks to address the issue of false alarms within FMCW systems by taking advantage of MIMO systems. MIMO stands for multiple input and output and are a staple modern technology. According to Kim and Kim (2018), “MIMO radars simultaneously propagate different waveforms from multiple transmit arrays to emulate a large virtual aperture with appropriate transmit spacing” (p. 1092). Kim and Kim (2018) also use code division multiplexing (CDM) to generate the waveform for the FMCW system. Combining FMCW radar with their proposed algorithm, MIMO radar, and copious amounts of DSP, their system produced promising results.

One of the major aspects of all FMCW systems is DSP. FMCW systems heavily rely on many spectrum analysis techniques since they are essentially encoded with frequency. Ju et al. (2014) dedicate an entire article to discussing implementing important FFT algorithms with an Altera Cyclone III FPGA, dedicated DSP processors, and supporting hardware such as ADC’s and DAC’s. The FFT and DFT are both incredibly important to FMCW systems, and references to such algorithms can be found in much of the literature surrounding the subject. Overall, FMCW systems have many applications to autonomous vehicles.

Conclusion

Radar systems are extraordinarily useful tools that have many applications. For autonomous vehicles, radars can help sense the environment surrounding the vehicle reliably and quickly. This allow the vehicle to ascertain the position of surrounding objects and helps the system to decide where to navigate and if there are any safety hazards. Radar units also are much more reliable that other systems since they are significantly less effected by weather and particles in the air.

The important radar technologies that support the radar system in autonomous vehicles are phased arrays and digital signal processing. These systems achieve the requirements for autonomous vehicle applications. Phased arrays are compact, have no risk of mechanical failure, and can scan can in three dimensions. Digital signal processing implements important tracking algorithms, filtering, and other control mechanism that could not be implemented by analog parts.

Overall, radar systems are important for the success and implementation of autonomous vehicles. Autonomous vehicles have the potential to revolutionize the transportation industry, commuting, and travel. However, they will go no where if they cannot properly detect and sense their environment. Technologies like LiDAR and ultrasonic sensors can help, but they do not achieve what radars can. Radar systems can easily meet the requirements for autonomous vehicles, and they are the path forward for autonomous vehicles.

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