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Application Note

RF System Design and Component Selection for a FMCW Radar System

Introduction

Since their initial development in the first half of the twentieth century, radar systems have become a vital part of modern life. With applications including detecting and guiding aircraft, observing weather, and exploring subterranean or otherwise inaccessible parts of the Earth as well as other celestial bodies, the development and proliferation of radar technology has had a profound impact on human life.

One radar system variety is a frequency modulated continuous wave (FMCW) radar system. This system operates by transmitting a constant signal and receiving a reflection of that signal. Because of the distance that it travels, the period of the reflected signal is shifted compared to the original signal. From this difference, the exact distance to the object causing reflection can be determined.

The design of a FMCW radar system requires some general elements: something to create the original signal, an apparatus to transmit the signal, a system to receive the reflected signal, and a system to process and compare the transmitted and received signals. Typical components include a modulator, a VCO, a power splitter, a transmitting RF amplifier, antennas for both transmitting and receiving, a receiving RF amplifier, a mixer, a baseband amplifier, a low pass filter, and an analog to digital converter. The radio frequency (RF) component of the design process for this system will be explored and detailed in the following sections regarding individual component selection.

Considerations for the Entire System

To begin designing a FMCW radar system there are several general, overarching considerations. The first and most obvious is choosing a frequency that all the individual RF components operate at. What is not so obvious about this selection is that there are legal restrictions on what frequencies can be used to avoid interfering with other signals. In the United States, certain frequency bands are allocated by the FCC for specific purposes and require a license to operate in; however, other frequency bands are allocated for hobbyists and other enthusiasts. As such, 2.4 GHz is a good selection for the operating frequency as this frequency is not restricted.

Next, there is the consideration of the system's power supply. When choosing different components, they may require different supply voltages. If you have components with different supply voltages, it follows that you need either multiple power supplies or circuits that can output and regulate a voltage different from their input. However, it is not necessarily efficient to use either of these methods. For instance, you may not have the luxury of having more than one available power supply. Also, having a circuit that transforms one voltage to another requires power and more components thus adding to the complexity and cost of the system. As such, it is desirable to have as many components as possible requiring the same supply voltage.

Additionally, the total cost of system is another general consideration. When designing a system, there is always some budget to consider. Subsequently, it is important to select components that will not exceed the budget. This is important in any stage of production of a system be it a prototype or commercial product.

Another general consideration is the noise in the system. Every component has some noise which can affect the performance of the system. Most component datasheets provide the noise figure (NF) of a component. This s related to another quantity, the noise factor (F), in the following way:

$$NF = 10\log(F)$$

From the noise factor, the total cascade noise figure (F_{CAS}) of a system can be estimated using the noise factor (F_1, F_2, etc.) and gain (G_1, G_2, etc.) of each stage:

$$F_{CAS} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$$

This cascade noise factor can then be converted to the total noise factor. Alternatively, some computer programs, such as Analog Device's ADIsimRF, can calculate the total noise figure based on the noise figure of each component.

One general consideration is the received power on the receiving side of the system. This power can be estimated by the following equation which is based on the radar range equation:

$$P_R = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R^4}$$

Where P_R is the received power, P_T is the transmitted power, G_T is the antenna gain of the transmitting antenna, G_R is the antenna gain of the receiving antenna, λ is the wavelength of the signal, σ is the radar cross section of the target, and R is the distance to the target object. Additionally, losses such as atmospheric loss can reduce the received power and should be considered depending on the scope of the radar system being used. It is important to ensure that the received power is strong enough to be processed in the rest of the system.

Also, you need to also consider how the system will be assembled. If you plan on assembling the RF components on one or more PCBs, it will be necessary to look for surface mount components for this purpose. Otherwise, you may choose to use components that are connected to one another by coaxial connectors; however, this will result in a heavier system. Other packaging for components may be available as well, such as plug-in components. As a side note, any components that are mentioned later will be surface mount components.

Other overarching considerations include the total weight of the system, the total power consumption of the system, and the time it takes to produce, prototype, and debug the system.

Selecting Individual Components

Next, the individual components of the system can be selected. Starting with the transmitting side of the system, the initial signal generation is of first concern followed by how the signal will be transmitted.

A modulator is needed to act as a function generator to generate the initial signal. One possible choice is to use a PJRC Teensy 3.1 microcontroller and a Microchip MCP4921 DAC. The Teensy 3.1 is coded to generate a digital signal which the MCP4921 uses to produce a triangle wave. These components were primarily chosen due to their availability, the fact that my group was familiar with them, and how my group felt that we were getting a good signal from them. Alternatively, the Teensy could have been used on its own as it has a built-in DAC; however, my group decided against this as we experimentally had some trouble producing a signal we liked.

Next, a VCO can be chosen. The VCO receives the generated signal which it modulates on a carrier frequency. One important parameter for a VCO is the phase noise which is noise caused by imperfections in generating a pure signal. If you were to look at the frequency spectrum of a VCO, you would observe some element of the spectrum outside of the ideal spectrum. To get a good signal, it is important to choose a VCO with low phase noise to reduce this non-ideality. Alternatively, you could use a filter to reduce any unwanted part of the signal, but that would require more power, circuitry, and possibly cost. Additionally, the power output of the VCO is important to consider. This parameter is important for the total signal power of the system. Also, having a larger output power may lessen the need for a more powerful amplifier later in the system thus possibly reducing the amount of power driving the system depending on how much power the VCO requires compared to similar VCOs. Another important parameter is the tuning voltage range. This range must encompass any range of voltages being inputted to the VCO. For this application, that means the output of the modulator. One choice of a VCO is the Minicircuits ROS-2536C-119+ which meets these considerations and those for the system in general assuming 5 volts is the typical input voltage.

To provide gain for the output signal, some sort of amplifier is needed. A low noise amplifier (LNA) is preferable in this case as this type of amplifier is designed to amplify a low-power signal without adding as much noise to it as other types of amplifiers would. The first area of concern for an LNA is the gain of the amplifier. You want to ensure that the transmitted power is powerful enough that you can properly receive it. However, LNAs have a limit to how powerful of an input signal they can amplify without distorting it. This occurs because amplifiers have a limited linear range after which they saturate. One important point is known as the 1 dB compression point and can either be noted as the input power at this point (IP1dB) or the output power (OP1dB). Knowing this point allows you to calculate when the signal will be distorted with a given LNA depending on the input to the LNA. As you probably want to maximize your transmitted signal power, you want to find an LNA that maximizes the total signal power without causing distortion thus you want an LNA with a high OP1dB. Various programs, such as ADIsimRF, can help calculate the maximum power that you can get from an LNA if you have its OP1dB and the strength of the signal being feed to it. Other considerations include the power used by the LNA, the noise figure of the LNA, and what frequencies it operates at.

Next, a power splitter can be chosen to split the original signal so that it can be both transmitted and used in the receiver to process the received signal. Beyond operating frequency, the most important consideration for a power splitter is how much it affects the signal. The power splitter will attenuate the signal, so choosing a power splitter with the smallest total loss for each port is ideal. For example, the BP2U+ power splitter from Minicircuits gets a total loss of between 3.3 dB and 3.6 dB for both ports over its operating frequency range.

For the antennas, there can be myriad considerations for what would be desired depending on how the system will be used and which antenna is being chosen: the transmitting or the receiving. However, the general notion is that the transmitting antenna can strongly transmit the signal and that the receiving antenna can easily receive the reflected signal. This notion can be met by considering antenna architecture. Additionally, how the antennas work together should also be considered as crosstalk between the two antennas may affect the performance of the radar system.

Now that the transmitting section of the system has been explored, the receiving end is of next importance. This part of the RF system deals with receiving the reflected signal and then processing it before sending it to a baseband circuit for further processing at low frequencies.

First, the signal must be amplified to be processed. This can be done using an LNA as before; however, because of the small received signal, higher gain is ideal in this section and distortion of the signal is of less concern. For instance, a PMA3-83LN+ LNA from Minicircuits provides a greater gain than the previously mentioned LNA model.

Next, an RF filter can be used to help remove any undesired signals. Although this may be unnecessary, an RF filter can help remove or reduce any extraneous signals from interfering with the reflected signal. The primary concern for an RF filter is its passband which must, at very least, span the possible range of frequencies that the system may use; however, the passband should ideally be larger than this but not so large that unwanted signals are not filtered out. Next, the loss from the filter should be minimized for the band of frequencies being used. One possible RF filter is the BFCN-2450+ from Minicircuits.

Following this, the mixer is the next component to be considered. In a mixer, you input two signals, the RF signal and the local oscillator (LO) signal, and receive an IF signal as an output. In this case, the RF signal is the received radar signal while the LO signal is the second output from the power splitter. The IF signal consists of two signals with two different frequencies: $f_{RF} – f_{LO}$ and $f_{RF} + f_{LO}$. The lower of the two frequencies, $f_{RF} – f_{LO}$, is the desired signal to be processed, so filtering will be needed to remove the other signal in the later baseband stage. Returning to choosing the mixer, there are several considerations to be made specifically for it. The first is the LO level. Mixers are specified by their LO level which translates to the ideal power of the LO signal inputted to it in dBm. For example, a level 10 mixer should ideally receive a 10 dBm signal. If there is no mixer with a level equal to the used LO power, it is recommended to choose a mixer with a level close to the actual LO level, preferably with a mixer level below the LO signal power. For example, an 8 dBm LO signal would work with a level 7 mixer. The next consideration is the isolation of the mixer. It is ideal to have a mixer that has good isolation between each port of it to reduce any signals from interfering with one another. Also, the conversion loss of the mixer which indicates how much of the input signal power is attenuated is another consideration with the lower loss being preferable. One example mixer that meets these specifications is the ADE-3G level 7 mixer from Minicircuits.

Additionally, it may be necessary to use attenuators to reduce a signal. For instance, this may be done to avoid distortion in a gain stage or to help match the power of the LO signal in the mixer to the level of the mixer.

Conclusion

When designing and building a radar system, there are many different considerations to be made. There are both general considerations for the system and specific considerations for each component used. For the RF portion of a FMCW radar system, there are considerations to be made for each component and how they relate to the whole system. As such, it is important to consider and weigh various characteristics of components when choosing them.