Economical, Modular COTS Radar

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***Abstract*—With the rapid development and advancement of commercial communications and wireless data transfer, the cost of components required to make a functional radar has rapidly decreased. Now more than ever, radar is available to the hobbyist. This work presents a radar design achievable with minimal cost, maximum flexibility, and minimum assembly time.**

***Keywords*— Radar, COTS, Frequency Modulated Continuous Wave, FMCW**

I. Introduction and Summary

As part of the "Radar 2020" International Radar Conference, a "Radar-a-thon" radar building competition is being held. The competition consists of a series of radar reflectors and calibration targets being hidden behind a curtain in a roughly 20-meter by 8-meter room. Entrants must use their system to describe what is behind the curtain. There are two levels of entry: less than 750 USD and less than 3000 USD. The design described in this paper will be submitted in the less than 750 USD category.

A modular design, versus "radar in a box" or "radar on a chip" solution serves to allow easier modification as well as illustrate to those new to radar each component in a physical manner. The selected design is Frequency-Modulated Continuous Wave (FMCW) and uses the audio card of a computer for digitization.

The design takes inspiration from [1], although with significant modifications. This paper explains in detail the drivers for the design, the design itself, and lists the specific components required for construction.

II. Fundamental Constraints

A. Cost

A fundamental requirement of the design is that the design must qualify for entry into the Radar 2020 "Radar-a-thon" competition category requiring a Bill of Materials (BOM) of less than 750 USD. The Frequently Asked Questions of the competition indicates that a mechanical positioner does not need to be included, and so the BOM is broken into two sections. The first lists only the components necessary for the radar and is less than the 750 USD constraint. For completeness, a second BOM for the gimbal as well as some optional, but convenient, components is included.

B. Time

An additional self-imposed constraint on the radar design is that construction of the radar, to minimal initial functionality, should be something achievable in a couple of weekends with no specialized equipment. While customized Printed Circuit Boards (PCB) are available via online providers, the proposed design only requires a prototyping board and minimal tools. The purpose of this constraint was to arrive at a design with the absolute minimum barrier to entry while still allowing for customization of individual components. While there are low-cost functional radars for sale, the ones reviewed by the authors did not allow for easy customization or design changes.

C. Testing Apparatus

In order to minimize complications and keep a low barrier to entry, the design was required to avoid custom Radio Frequency designs. System performance should be predictable without specialized antenna testing chambers or any equipment more sophisticated than a low-end oscilloscope. The result of this constraint is the use of components and antennas that come with standard 50-Ohm connectors from the manufacturer. While hobbyists certainly can, and do, build custom antennas that function, the proposed radar design relies on purchased antennas with data sheets to avoid the risk of having a custom antenna with an unknown and potentially problematic pattern.

III. Principle of Operation

A. Frequency Modulated Continuous Wave

The principles of FMCW are described succinctly in [2] and will not be repeated in full detail here. The basic principle is that by transmitting a swept FM waveform, and mixing the received signal with the transmitted signal, range delay is turned into a "beat" frequency at much lower frequencies than the carrier. The first reason for FMCW is that Continuous Wave systems are 100% duty factor which helps with recovering signal when low transmit powers are a limitation. As is explained below, FCC compliance drives very low transmit powers.

The second, and more critical, reason for selection of FMCW is that the design very easily allows for use of a wide-band waveform without requiring wideband digitization. Due to the constraints explored above, the authors did not want to require use of an ADC more complicated than that provided by the microphone or audio input port of a computer.

B. Radar Range Equation Calculations

The Radar Range Equation allows for rough, first estimate calculations to provide some assurance that a design is feasible. A modified form of the equation is:

$$R = \sqrt[4]{\frac{ERP * G_r \lambda^2 \sigma}{SNR * (4\pi)^3 k T_0 B F L}} \qquad (1)$$

Where R is the detection range in meters, ERP is the Effective Radiated Power in Watts, G_r is the receive gain and is unit-less, λ is the wavelength in meters, σ is the Radar Cross Section in

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square meters, SNR is the Signal to Noise ratio required for detection and is unit-less, k is Boltzmann's constant, T_0 is noise temperature in Kelvin, B is the inverse of the FM sweep duration and is in Hertz, F is the noise figure and is unit-less, and L is system losses and is also unit-less. The values listed in Table I yield a predicted detection range of approximately 20 meters.

Note that the values are listed in a convenient format and must be converted to the units listed above for use in (1).

TABLE I. RADAR RANGE EQUATION VALUES

Radar Range Equation Values		
Parameter	***Value***	***Notes***
ERP	-71.3 dBW	Required by FCC
G_r	22 dBi	Limited by far-field
λ	5.5 cm	Corresponding to 5.45 GHz
σ	1 m^2	
SNR	15 dB	Likely higher than necessary
k	$1.38 * 10^{-23}$ J/K	
T_0	290 K	
B	33 Hz	Corresponding to 0.03 s sweep duration
F	6 dB	Noise figure of ZX60-V62+
L	8 dB	Contains both losses and integration gains, tunable via increasing number of sweeps integrated

As noted in Table I, the loss parameter is being treated as a tunable parameter due to the losses of the full system being unknown. However, by integrating multiple sweeps, the SNR can be increased which can be included as a reduction of the losses. The end design can integrate as long as necessary to see smaller targets or increase the detection range.

While the Radar Range Equation give ranges for detecting targets that are limited by thermal noise, the stationary targets in the room will be indistinguishable from clutter. Thus, the reflector's Signal to Clutter Ratio (SCR) will ultimately limit the ability of the system to find a stationary radar reflector. A triangular wave fed to the Voltage-Controlled Oscillator (VCO) will allow the radar to measure target Doppler and distinguish moving targets from clutter. Clutter will be present given that the target scene will be indoors.

IV. SYSTEM DESIGN

A. Radio Frequency Stage Design

Fig. 1 shows the design of the RF stage. The FMCW implementation is quite simple and can easily be implemented with packaged components from www.minicircuits.com. The BOM included at the end of this paper shows the specific components selected for the design. The center frequency was selected to be in the 5-GHz Wi-Fi band due to the availability of cheap, high-gain (directional) antennas of reasonable size. All of the RF components, except the antennas, are capable of 4300-MHz to 6000-MHz operation. The antennas are likely capable of similar operation, but will have different gains and beam shapes due to the change in wavelength across those frequencies.

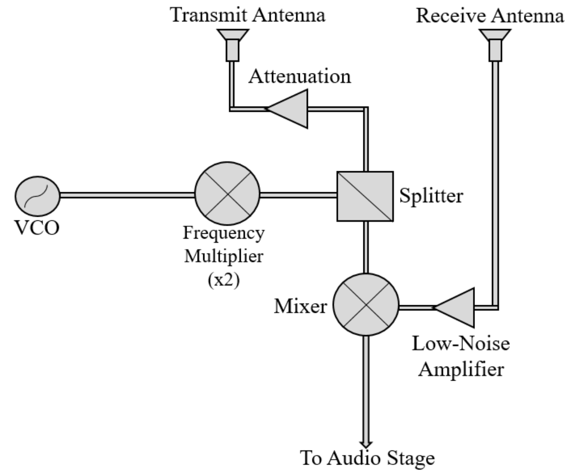


Fig. 1. RF Stage Design.

Highly directional antennas were selected in order to both increase the receive gain to compensate for the ERP limitations and to help minimize the amount of clutter in a given beam position. Initially 30-dBi antennas were considered; however, given that the expected target scene would be at most 20-meters deep, the high gain meant that the entirety of the scene would be within the Fraunhofer distance and may have reduced gain and unexpected patterns. Therefore, 22-dBi antennas were selected which place most of the scene in the far-field antenna region. The directional antennas will also help place targets in the angular, or cross range dimension. The design allows for accuracy finer than a single beam width via amplitude comparison for sufficiently strong targets. While the radar should, in theory, support Synthetic Aperture Radar (SAR) operation, none was planned for in the initial design.

B. Waveform Design

The primary constraints driving the waveform design are based on the expected scene (target set) and bandwidth of the RF components. The closest target is expected to be around 2-meters from the antennas and the farthest around 20-meters from the antennas. The best possible range resolution is desired as finer resolution will aid in distinguishing radar reflectors in the scene from area clutter. Finer range resolution will also help to resolve reflectors at the longest ranges where the antenna beam will likely be illuminating multiple reflectors. In order to keep the close-range targets away from the signal—which will be directly coupled between the transmit and receive antennas—the FMCW slope must be sufficient to give target 2 meters away a response greater than 500-Hz. Therefore, the slope of the FM waveform must be at least 37.5-GHz/s. Coincidentally, since a long slope is desired to put more energy on target, having a wider sweep bandwidth both increases range resolution and allows for a longer sweep, given the slope requirement.

The authors plan for a triangle waveform driving the VCO in order to measure Doppler, but for initial testing a sawtooth-type waveform will be utilized. For a sweep bandwidth of 1-

GHz, the sweep duration needs to be no longer than approximately 27-milliseconds.

C. *Federal Communications Commission Compliance*

The design, being a home-built device, falls under FCC Part 15.23, which mainly allows for an RF device that does not require authorization as long as good engineering practices are followed to ensure the remaining standards are met [3].

Additionally, due to the wide bandwidth requirement driven by the expected target set, the radar design falls under Part 15.5 for Ultra-Wideband (UWB) operation. Depending on the exact final design and use, the radar could be considered an indoor, surveillance, or imaging UWB system. The VCO and frequency multiplier set the RF minimum and maximum. For the sake of FCC compliance, the full bandwidth will be considered. Using the Mini Circuits part ZX95-3050A+ with a frequency multiplier ZX90-2-36-S+, the minimum is approximately 4000-MHz and the maximum is approximately 6500-MHz. The frequency range is allowable under the UWB requirements, which impose Effective Radiated Power (ERP) limits of -41.3-dBm [3]. Compliance is achieved through the use of attenuation between the splitter and antenna. The datasheet of the VCO lists 7-dBm output power, and the frequency multiplier datasheet lists a typical conversion loss of 11-dB. With an ideal splitter reducing the power by 3-dB and the use of a 22-dBi antenna, an additional approximately 56.3-dB of attenuation is required. The splitter insertion loss is listed as 0.8-dB nominally, so 57-dB of attenuation between the splitter and transmit antenna should be sufficient while still providing compliance margin. 60-dB of attenuation on transmit was used in the actual implementation.

Finally, the use of packaged COTS devices with datasheets for all the RF components helps ensure that emissions are within the frequencies designed.

D. *Audio Stage Design*

The FMCW design requires a waveform generator to drive the VCO and some filtering and digitizing after the mixer in order to perform signal processing. For ease of use, waveform flexibility, and to minimize the parts required, the design places the received signals in the audio range. Therefore, the audio input or microphone port of a standard computer can be used to digitize the return signal. Similarly, the design uses the audio output of a computer in order to drive the VCO.

On receive, the output of the mixer goes through an amplification and low-pass filtering stage to eliminate the upper high frequency mixing product and prevent aliasing. The authors selected an 8-pole low-pass filter chip. A high-pass filter, which will be constructed with Sallen-Key topology, then filters out the low frequency power caused by direct transmit antenna to receive antenna propagation. Finally, a simple voltage divider protects the microphone input from damage. Fig. 2 shows the basic design.

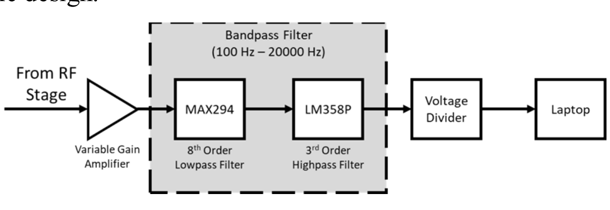


Fig. 2. Receive Audio Stage Design

On transmit, the audio output goes through an envelope detector (full wave rectifier and low pass filter) before being amplified and shifted in voltage in order to drive the VCO with the correct levels to produce the desired waveform. The envelope detector will allow somewhat arbitrary waveform generation by controlling the amplitude modulation of the audio output of the computer. Fig. 3 shows the basic design.

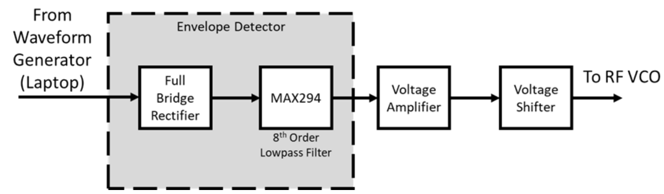


Fig. 3. Waveform Generation Stage Design.

E. *Positioner Design*

The radar design up to this point is capable of range, and theoretically range-rate, measurement. In order to position the returns in three-dimensional space, azimuth and elevation must also be measured. SAR allows essentially arbitrary accuracy depending solely on the distance traveled to synthesize the array. While the design is theoretically capable of SAR, SAR was not selected for three main reasons: complexity, cost, and unknown setup space. SAR requires more processing as well as components to precisely measure the location of the radar antennas, both of which increase cost and complexity. Additionally, since detail was not given for how much space there will be for the radar to move while looking through the curtain at the scene for the competition, the authors thought there would be too many unknown variables.

Instead, the extra two dimensions will be measured via an instrumented security camera turret. Hall effect sensors can be mounted to the positioning gears of the turret to count gear teeth; by accumulating gear teeth combined with knowledge of the direction of movement, the position of the gimbals can be assessed and reported to the computer. The computer will then have access to both the range/range-rate from the radar signal processing and the azimuth/elevation position of the gimbals. The computer can then display, in real time, the three-dimensional position of returns. By oscillating the turret around a detected reflector, more angular measurements can be made with higher precision than the antenna beamwidth.

V. SYSTEM GROWTH CAPABILITY

The cost of the design is shown on the attached BOMs, both with and without the positioner/turret. The cost increased somewhat with the use of discrete packed RF components, but the advantage of such a design is that components can very easily be swapped since everything has a standard connector. Also, for those new to radar, there is a pleasing visual connection between each piece of the RF block diagram and the physical components. The authors intend to enhance the system beyond the Radar 2020 competition by implementing more sophisticated waveforms (easily done via software only due to the “exciter” design) as well as implementing a SAR capability.

The authors had originally considered a design be centered around 15-GHz due to the low cost of satellite TV antennas, but all the parabolic dishes at low prices had receivers integrated into the dish feeds; thus the 5-GHz band was selected. Higher frequencies would be more advantageous for the Radar 2020 competition setup, but the authors wanted a design that was cheap and expandable in order to work as a demonstration and training radar for those new to the radar industry.

VI. Experimental Results

The authors found during physical implementation of the design and initial testing that some design changes were required. The design was not entirely completed due to the COVID-19 lockdown and restrictions, but initial testing showed that the fundamental design would work. The following sections detail the deviations from the original design described above and show the initial test results.

A. RF and Receiver Design Changes

The relatively inexpensive RF amplifier selected (ZX60-V62+) was not providing enough gain on receive, and so ultimately two of the amplifiers were cascaded on receive between the receive antenna and the mixer. Additionally, interference was appearing when the radar strayed into the 5.8 GHz WiFi band. The authors assume that the low ERP of the system meant that even though a wide band waveform was used the spikey interference caused too much noise. Therefore, the successful testing limited the system to approximately 4 GHz to 5.6 GHz. The interference seen above 5.6 GHz was assumed, but not proven, to be WiFi, as the authors lacked the test equipment to observe RF above 3 GHz.

The second audio channel from the computer output was intended as a synchronization channel. However, the microphone input on the test laptop turned out to only record a single channel. So, the receiver was modified to add a voltage summer right before going to the microphone input. Thus, one channel of the computer output an initial synchronization sequence before the other channel began the AM signal. By combining the two channels in a voltage summer, the variable delay in the output of the sound card could be detected and removed from the received signal.

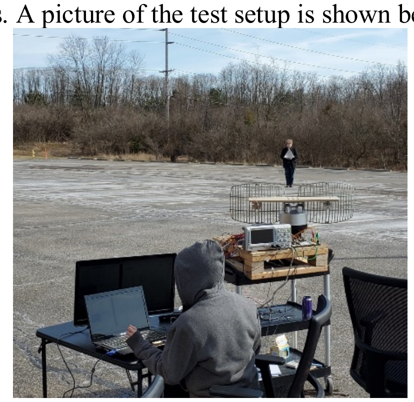
Additionally, the 3rd order High Pass Filter was omitted from the final receiver design and instead of a variable amplifier in the receiver, a fixed amplification stage was designed.

B. Waveform Design Changes

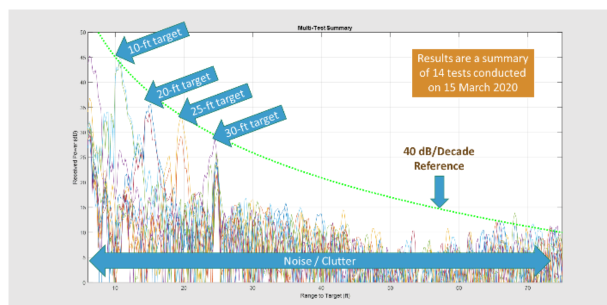
The selected VCO was not handling the rapid control signal changes driven by the originally planned 0.03 second ramp duration. Thus, the team ultimately switch to a much shallower and longer sweep for each tooth of the sawtooth waveform. The best results were seen when sweeping 1.6 GHz over a 0.5 second ramp, leading to a slope of 3.2 GHz/s. The longer duration effectively allowed for coherent integration.

C. Test Setup and Initial Results

While COVID-19 restrictions prevented completion of the system and testing, some initial results showed success. The test involved a cardboard trihedral reflector lined with aluminum foil being held by a person at varying distances in a parking lot. An exterior environment was selected for the initial testing to minimize clutter caused by propagation through walls. A picture of the test setup is shown below.



The post processed results are shown below, with the target reflector clearly visible through 30 feet.



References

[1] G. W. Stimson, H. D. Griffiths, C. J. Baker, and D. Adamy, Stimson's Introduction to Airborne Radar. Edison, NJ: Scitech, 2014.

[2] G. L. Charvat, "Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging". Massachusetts Institue of Technology. https://ocw.mit.edu/resources/res-ll-003-build-a-small-radar-system-capable-of-sensing-range-doppler-and-synthetic-aperture-radar-imaging-january-iap-2011/

[3] Electronic Code of Federal Regulations, TITLE 47, CHAPTER 1, SUBCHAPTER A, PART 15.

Design Section	Name	Model Number	Source	Quantity	Price Per Unit (USD)	Total (USD)
	Radar Bill of Materials					
RF	VCO	ZX95-3050A+	www.minicircuits.com	1	90.95	90.95
	Frequency Multiplier	ZX90-2-36-S+	www.minicircuits.com	1	36.95	36.95
	Splitter	ZX10-2-722-S+	www.minicircuits.com	1	35.95	35.95
	Mixer	ZX05-63LH-S+	www.minicircuits.com	1	47.95	47.95
	Adapters	SM-SM50+	www.minicircuits.com	5	5.95	29.75
	RF Amplifiers	ZX60-V62+	www.minicircuits.com	2	49.95	99.90
	30 dB Attenuator	VAT-30+	www.minicircuits.com	2	13.95	27.90
	22 dBi Antenna	HG5822EG	www.amazon.com (Potomac eStore listed on Amazon)	2	24.95	49.90
	SMA to Type N Cable	None	www.amazon.com	2	12.59	25.18
	RF Subtotal					444.43
Audio	*Low Pass Filter*	MAX294CPA+	www.digikey.com	2	8.53	17.06
	Headphone Jack Breakout	1699	www.adafruit.com	2	0.95	1.90
	3.5mm Audio Cable	876	www.adafruit.com	2	2.95	5.90
	Op Amp	LM358P	www.digikey.com	6	0.35	2.10
	Op Amp	OPA2134	www.digikey.com	2	4.79	9.58
	Audio Subtotal					36.54
Miscellaneous	*12 V Tractor Battery*	None	Home Depot	1	50.00	50.00
	5-V Regulators	MC7805BTG	www.digikey.com	4	0.63	2.52
	Consumables (solder, wood for mounting antennas, nuts, bolts, etc.)	None	Home Depot www.digikey.com www.arrow.com			50.00
	Resistor and Capacitor Kits	None	www.digikey.com www.microcenter.com	2	15	30.00
	Misc. Discrete Components (Potentiometer, Switch, Wire)	None	www.digikey.com www.microcenter.com			50.00
	Miscellaneous Subtotal					182.52
	Radar Total					**663.49**

	Optional Radar Bill of Materials					
Design Section	***Name***	***Model Number***	***Source***	***Quantity***	***Price Per Unit (USD)***	***Total (USD)***
Optional Additions	*Banana Cable Set*	None	www.amazon.com	2	12.99	25.98
	Banana Plug Socket Set	None	www.amazon.com	4	7.99	31.96
	Headphone Jack Breakout	1699	www.adafruit.com	4	0.95	3.80
	3.5mm Audio Cable	876	www.adafruit.com	2	2.95	5.90
	Cardboard and Aluminum Foil for Reflectors	None	Wal-Mart			10
	Optional Subtotal					77.64
Gimbal	*Turret*	82-12440	www.newark.com	1	68.89	68.89
	Hall Effect Sensor	55505-00-02-A	www.digikey.com	2	21.56	43.12
	Raspberry Pi 3b+	601561	www.microcenter.com	1	29.99	29.99
	Relay Hat	None	www.sequentmicrosystems.com/	1	35	35.00
	24VAC transformer	B01HPJT7C0	www.amazon.com	1	13.58	13.58
	Power Plug	B01N38H40P	www.amazon.com	1	4.95	4.95
	9 Conductor Wire	B0798SXH7K	www.amazon.com	1	22.95	22.95
	Power Supply	RD-50A-VP	www.amazon.com	1	17.61	17.61
	Plugs, Sockets, Barrier Strips, Power Spreaders	None	www.digikey.com			35.00
	Gimbal Subtotal					271.09
	Optional Total					**348.73**