Reconfigurable FMCW Resolution Improvement Using Adaptive Cancellation

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***Abstract*— Frequency-modulated continuous-wave (FMCW) radar enables target ranging using microwave signals. However, stationary clutter can obscure targets and affect radar performance in complex environments. The existing clutter removal techniques rely on target motion or open-loop correction, making them unsuitable for stationary targets or for long-term operation. This work presents a novel radar system that actively removes clutter using adaptive RF feedforward cancellation. By operating in the RF domain, clutter effects are mitigated without increasing the computational load of the system. The proposed system is simulated and experimentally implemented, demonstrating effective clutter cancellation without compromising radar sensing capabilities.**

***Index Terms*— Clutter cancellation, frequency-modulated continuous-wave (FMCW) radar, radar systems.**

I. Introduction

FREQUENCY-MODULATED continuous-wave (FMCW) radars have quickly become an attractive solution for numerous ranging and sensing systems. New developments in automotive radar [1], [2], industrial sensing [3], [4], physical activity monitoring [5], [6], and home health tracking [7], [8] that leverage FMCW radar are rapidly emerging. FMCW range detection is accomplished by transmitting an electromagnetic wave, whose frequency is modulated periodically [9], [10]. This variable frequency wave propagates through the environment and is scattered by targets and clutter in the sensing environment. This scattered signal is then downconverted by the radar receiver. For FMCW radar using a ramp waveform, the time delay caused by propagation and electronic delay produces a beat frequency in the baseband spectrum proportional to the range of the target. However, stationary clutter at a range similar to that of the target produces a similar beat frequency, making it difficult to resolve the target from clutter [11]. The fast Fourier transform (FFT) may be used in both the fast-time and slow-time dimensions in order to extract both the range and Doppler information of moving targets, allowing them to be resolved even if they would normally be concealed by stationary clutter. This technique, however, requires that the target maintains motion [12], which is not practical for many applications. Computationally intense techniques may be used to suppress clutter [13]; however, a strong clutter signal can still impact detection ability if the receiver is overdriven. Previous works have shown that RF feedforward is capable of suppressing self-interference but have not shown the ability to cancel the effects of stationary clutter located away from the sensor [14]. Beamsteering may be used to provide angular resolution [15], [16], [17] but requires many antennas and increases the system's size and power use.

Manuscript received 15 August 2023; revised 17 October 2023, 13 December 2023, and 2 February 2024; accepted 28 February 2024. Date of publication 22 March 2024; date of current version 10 May 2024. This work was supported by the National Science Foundation (NSF) under Grant ECCS-2028863 and Grant ECCS-2112003. *(Corresponding author: Aaron B. Carman.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LMWT.2024.3375790.
Digital Object Identifier 10.1109/LMWT.2024.3375790

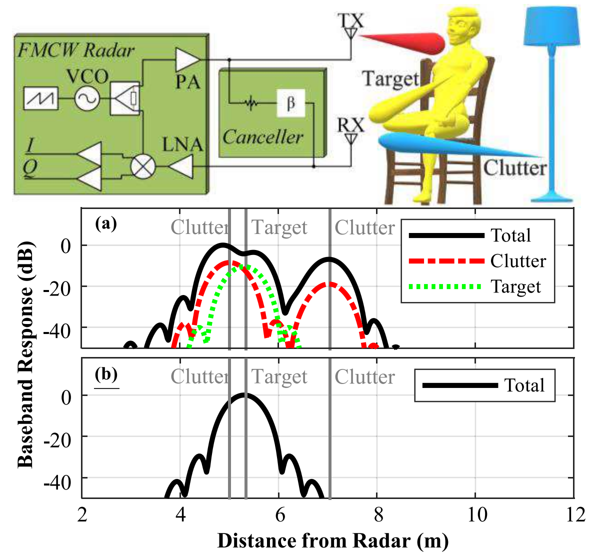

Fig. 1. Example FMCW active clutter cancellation system negating the impacts of clutter on FMCW ranging through adaptive cancellation at the transceiver.

This work presents a novel clutter cancellation technique that utilizes adaptive RF feedforward to achieve dynamic clutter compensation and improve the detection abilities of FMCW radar in practical applications. Clutter cancellation is achieved by controlling the amplitude and time delay of a feedforward signal to negate the effects of stationary clutter in the RF domain without either increasing the data processing load or restricting the radar's operating point. The theory of adaptive cancellation is presented and then examined through a time-domain FMCW radar simulation. The theory is verified experimentally using a passive canceller to provide the time and amplitude shift to negate the effects of stationary clutter.

II. Theory

In FMCW ranging radar, the finite bandwidth of the sensor imposes limitations on the range resolution of the sensor that can obscure targets in the presence of strong static clutter [18]. In an FMCW radar system without clutter

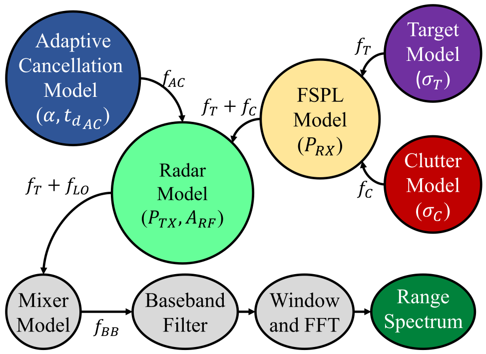

Fig. 2. Simulation flowchart used to evaluate the impact of adaptive cancellation on FMCW radar detection.

cancellation, a strong static clutter creates an area of low resolution in the range spectrum illustrated by Fig. 1(a), where the target signal cannot be effectively resolved. Even with sufficient range resolution, a strong clutter signal can impact the detection ability of the radar by reducing the maximum gain before saturating the receiver and preventing weak target signals from being detected. If, however, a system including a canceller illustrated in Fig. 1 is employed, clutter cancellation may be performed at the RF front end by combining the received signal with a delayed and attenuated copy of the transmitted signal to destructively interfere with only the clutter's backscatter, producing the spectrum shown in Fig. 1(b) and isolating the signal produced by the target. In this system, detection can be performed in the presence of clutter while maintaining simple signal processing requirements and boosting the effective range resolution of the sensor. It is worth noting that although full cancellation may require a polarity change, effective cancellation can be performed if the bandwidth is sufficiently low relative to the chirp period, as will be evident through simulation and experimental results with realistic bandwidth values.

III. System Simulation

In order to evaluate the impact of the theoretical cancellation technique, a simulation is developed to allow for rapid parameter adjustments. The overall simulation block diagram is illustrated in Fig. 2. Based on the desired target and clutter ranges and radar cross section (RCS) values, the FSPL, target, and clutter models solve for the relative power of the signals received from the target and clutter using the formula

$$P_{\mathrm{RX}} = \frac{P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}} \sigma \lambda^2}{(4\pi)^3 R^4} \tag{1}$$

where P_{TX} is the transmit power, G_{TX} and G_{RX} are the transmit and receive antenna gains, respectively, σ is the RCS, λ is the free space wavelength, and R is the distance. Given the clutter's location, the adaptive cancellation model finds the required time delay and linear attenuation to cancel the clutter using

$$\alpha = \frac{P_{\mathrm{RX}_C}}{P_{\mathrm{TX}}} \tag{2}$$

$$t_{d_{\mathrm{AC}}} = \frac{2R_C}{c} \tag{3}$$

where P_{RX_C} and R_C are the power received from the clutter and the clutter distance, respectively, and c is the speed of light. Radar parameters, such as bandwidth, transmit power, and receiver gain, are then used to synthesize the resulting time-domain LO signal and to calculate the received time-domain RF signals from the target, clutter, and canceller using

$$v_{\mathrm{RX}}(t) \propto \sqrt{50 P_{\mathrm{RX}}} \cos\left(2\pi\left(f_C + \frac{B}{2}t\right)(t - t_d)\right) \tag{4}$$

for each received signal, where B is the radar bandwidth. The RF signal is then downconverted to create a baseband time-domain signal. Digital filtering followed by windowing and FFT creates the final range spectrum for evaluation. The simulation is first tested assuming a radar with a 5-dBm transmit power, antenna gains of 6 dBi, and a 400-MHz bandwidth and corresponding 0.375-m range resolution without feedforward cancellation. The response is simulated with a target at 5.3 m from the radar and two clutters with a 1-m^2 RCS at 5 and 7 m. The resulting range spectrum is shown in Fig. 1(a) along with the spectra for both the target- and clutter-only cases. It is seen from the results that the target cannot be resolved when its absolute distance to the radar is near that of the clutter due to limited range resolution. By precisely controlling the delay and attenuation of the feedforward path, however, the clutters' response can be removed to improve the range resolution. A second simulation including a cancellation signal is implemented to verify this theory, producing the range spectrum shown in Fig. 1(b). These results illustrate that the target distance can be clearly extracted after removing the impact of multiple clutters without requiring an increase in computational load or sensor complexity.

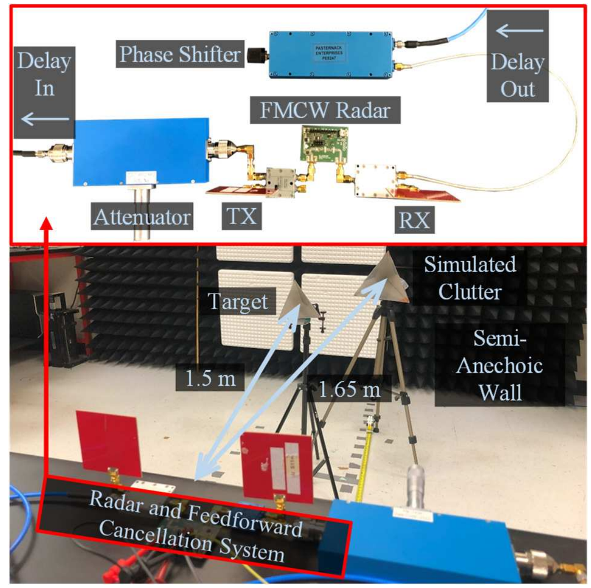

Fig. 3. Experimental setup to measure the impact of feedforward cancellation on detection ability near clutter.

IV. Experimental Verification

A. Experimental Setup

In order to verify the theory behind the proposed clutter cancellation technique, a simplified experiment is developed. The experimental setup uses an FMCW radar system developed in [19], which leverages an Analog Devices HMC358 VCO alongside variable microwave passive components to realize a manually tunable system. The experimental radar system alongside the feedforward components is shown in Fig. 3 with a corresponding block diagram. At the radar's transmit

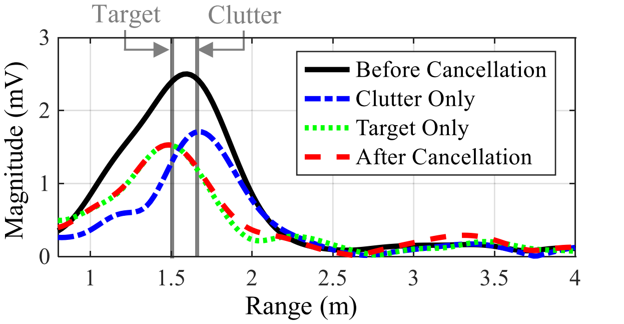

Fig. 4. Range spectrum evaluating the performance of adaptive cancellation. After enabling the feedforward loop, the measurement matches the ground truth and resembles the ideal signature of the target.

port, the chirp signal is evenly divided into the antenna and feedforward paths. The antenna path is connected directly to a 2 × 2 horizontally polarized patch antenna array with a gain of 5 dBi, an effective aperture of 6.28 cm^2, and a 3-dB beamwidth of 20°, which will radiate energy into the environment, while the feedforward path consists of 1.8 m of transmission lines to realize the necessary time delay. In addition, a 2–18-GHz variable attenuator and dc to 18-GHz phase shifter in the feedforward path provide fine amplitude and delay adjustments to precisely match the response of the target and set the bandwidth of the cancellation path to 16 GHz. Backscattered energy from targets and clutter detected by another 2 × 2 patch antenna array at the receiver and is combined with the output of the feedforward path after delay and attenuation. The feedforward attenuation and fine time delay are then adjusted manually after placing a clutter to minimize its response in the baseband spectrum. In a practical system, however, this can be accomplished using an electronic attenuator and phase shifter to remove the manual adjustment step. If the delay and attenuation are precisely adjusted to provide destructive interference throughout the chirp, the cancellation of the clutter signal occurs at the receive port, negating its impact on a purely analog fashion at the RF front end. As such, it is expected that the impacts of clutter on target detection and range resolution will be completely removed, allowing for accurate target range measurements in the presence of clutter.

B. Experimental Results

The FMCW radar from [19] is driven with a sawtooth signal creating a chirp that occupies a bandwidth from 5.65 to 6.25 GHz (600-MHz bandwidth) with a repetition frequency of 1 kHz. To quantify the impact of the cancellation signal on the sensor's performance, baseline measurements are first taken without the cancellation hardware and then repeated with the feedforward cancellation path enabled. The measurements taken include a corner reflector 1.65 m from the radar acting as a piece of clutter, a second, smaller corner reflector 1.5 m from the radar acting as the target, and the response with both the target and clutter at their respective locations approximately normal to the plane of the radar antennas with slight offsets to prevent obscuring the target or clutter. Fig. 3 provides an image of the experimental setup used to provide feedforward cancellation, in addition to the locations of the target and clutter reflectors in the sensor's field of view. The resulting range spectra from the measurements are illustrated in Fig. 4 alongside the ground truths for the clutter and target locations. Before the cancellation loop is enabled, the range spectrum with both target and clutter (solid curve) cannot resolve the target or clutter ranges, limiting the accuracy and range resolution of measurements near strong static clutter. It is seen that the measurement before cancellation very nearly matches the sum of the measurement with clutter only (dotted-dashed curve) and the measurement with target only (dotted curve), illustrating the impact of limited range resolution on measurements near clutter. After enabling the feedforward cancellation loop, the new spectrum with both the target and clutter (dashed curve) can effectively resolve the target's true location despite the presence of clutter near the target. In addition, the measurement almost exactly matches the response of the target-only case, demonstrating that feedforward cancellation can remove the impacts of clutter in such a way that a target can be measured and resolved as if no clutter were present. As such, the proposed technique is shown to improve accuracy, range resolution, and detection ability for FMCW radars using simple signal processing techniques. Using the current system, however, only a single clutter can be canceled, and an increase in clutter distance would proportionally increase the length of the delay line required, limiting the practical applicability of the system. As such, in order to provide enhanced versatility, future systems using this technique could include multiple cancellation paths and software-controlled board-level time delays instead of transmission lines in order to negate these limitations.

V. Conclusion

In this work, a reconfigurable feedforward clutter-canceling FMCW radar system is presented as a method for stationary clutter removal and range resolution improvement in realistic sensing environments. The system leverages a feedforward signal path to provide time delay and amplitude shifts to cancel the effects of clutter in the RF domain and improve the radar's range resolution and detection accuracy near clutter. A time-domain FMCW radar simulation demonstrates the effectiveness of a theoretical system leveraging adaptive cancellation to destructively interfere with the clutter signal in the analog domain. An FMCW radar system leveraging feedforward cancellation is tested in an experimental setup, where a combination of delay lines, variable attenuators, and phase shifters creates fine time and amplitude shifts to precisely cancel the effects of clutter. Results show that the system removes the effects of clutter in the radar's resulting range spectrum providing improved range resolution without increasing the used bandwidth. Furthermore, after cancellation, the response of a target near clutter nearly exactly matches that of a target in an uncluttered environment, demonstrating the effectiveness with which adaptive feedforward cancellation removes clutter effects. Future works should further develop the system to include electronically tunable amplitude and time shifts for integration in a complete sensor, as well as the development of a board-level canceller that can automatically cancel stationary clutter effects to adapt to a variety of sensing scenarios.

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