

Frequency Modulated Interrupted Continuous Wave Signals in Different Radar Imaging Applications

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Abstract

Undesired reflections at the interface between air and other materials can compromise the detection of targets and saturate and block the receiver in a variety of radar systems for applications such as through-wall imaging, ground penetration radar, and medical imaging. In this paper we propose a technique based on frequency modulated interrupted continuous wave (FMICW) signals as a novel approach to mitigate/remove the undesired reflections. The proposed technique has been successfully validated through different in-field experiments performed with a radar system built for the purpose.

1. Introduction

Ultra Wide Band (UWB) radar systems have been successfully demonstrated for a variety of imaging applications such as through-wall detection [1], Ground Penetration Radar (GPR) [2], and medical imaging for breast cancer detection [3]. UWB waveforms can provide fine resolution for imaging purposes and suitable penetration through a variety of materials, like different types of walls and soils, or human skin and tissues, depending on the chosen frequency range. Low operational frequency is desired to reduce propagation losses through the materials, but this implies larger and heavier antennas which may not be appropriate for in-field applications.

A main problem of the aforementioned applications is the near-far problem where the transmitter-receiver coupling and the undesired reflections from the interface between air and another material can be significantly stronger than the backscattered signal from potential targets, which are therefore masked and hard to detect. This undesired contribution can be for instance wall reflections for through-wall radar systems, ground reflection for GPR, and skin reflection for medical applications. The presence of strong undesired signals also limits the dynamic range of the radar system and increases the possibility of saturating and blocking the receiver.

Different techniques have been presented in the literature to mitigate/remove the undesired contributions, for instance subspace projection, spatial filtering, change detection for through-wall detection of moving targets, and band-pass filtering [4]. In this paper we present an alternative technique to tackle the aforementioned near-far problem based on frequency modulated interrupted continuous wave (FMICW) waveforms. Although used in the past for ocean sensing radar systems and ionospheric channel sounding, these signals have not been used yet for the proposed radar applications to the best of our knowledge. Unlike methods applied at the post-processing phase after the digitization of the signal (subspace projection, spatial filtering, estimation and subtraction of the undesired components from the received data), FMICW waveforms are a hardware approach which mitigates/removes the undesired components before digitization, thus avoiding the reduction of the system dynamic range and the possibility of blocking the receiver. The proposed technique can also be combined with the aforementioned methods in order to remove residual clutter and undesired contributions, thus improving the overall performance of the system.

The paper is organized as follows. In section 2 an analytical description of FMICW signals is provided. In sections 3, 4, and 5 the proposed technique is experimentally validated in different scenarios and applications. Finally section 6 concludes the paper.

2. FMICW description

FMICW signals can be generated by switching on and off with complementary sequences the receiver and the transmitter of FMCW radar systems. Binary functions multiplying the transmitted and received FMCW

signals provide a mathematical model of these gating sequences, as the transmitter/receiver is on when the value of the sequences is 1 and off when the value is 0 [5]. The cross-correlation between the sequence $g(t)$ used at the transmitter and the complementary sequence $1-g(t)$ used at the receiver is called mean received signal (MRS) and is useful to understand the effect of applying the gating sequences [5]. The MRS depends on the round-trip delay τ , i.e. the time for the transmitted signal to reach the targets and be reflected back to the receiver, and on the bit duration of the sequence T_b . The MRS can be considered as a delay-dependent weight applied to the overall received power of the radar system, i.e. at some values of round-trip delay (the so-called blind ranges) the MRS pattern provides additional attenuation as the receiver is not active. It is therefore possible to design MRS patterns suitable for removal of undesired contributions in radar imaging systems by carefully selecting the parameters of the gating sequences (number of bits, bit duration, duty cycle) for FMICW waveforms. Fig. 1 shows the MRS patterns of two gating sequences which are used on the experimental data presented later in this paper, namely a square wave and a 3 bit M-sequence. The two additional delays are used to change the duty cycle of the gating sequence used at the receiver, therefore extending the blind ranges in the MRS for better removal of undesired components. However, the additional off-time at the transmitter and at the receiver reduces the signal-to-noise ratio (SNR) and therefore a compromise must be sought [4].

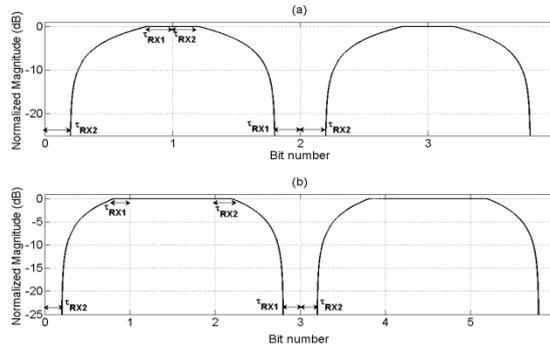


Fig.1 MRS of the square wave (a) and of the 3 bit M-sequence (b)

3. Experimental Validation for Through-Wall Imaging Applications

Experiments for through-wall detection have been performed in realistic environments at the School of Engineering and Computing Sciences, Durham University, with different kinds of walls, namely an 8 cm thick plastered plywood wall, a 16 cm thick plastered bricks wall, and a 15 cm thick concrete blocks wall. The radar system employed for these experiments is based on arbitrary waveform generators (AWG) to create FMICW signals and modify flexibly parameters such as bandwidth and duration of the FMCW waveform and the features of the gating sequences. A detailed description of the radar system and its specifications is provided in [4].

The experiments aimed at the through-wall detection of several stationary objects and people moving or breathing. For the stationary case, the synthetic aperture radar (SAR) approach has been used, with the transmitting and receiving antenna placed 20 cm apart and moved along an array of 7 different positions, which are located 10 cm apart. Fig. 2 shows an example setup with a target (a cake tin) on the left-hand side and the antennas and part of the radar system mounted on a trolley behind the brick wall on the right-hand side. Fig. 3 presents the corresponding radar images obtained with FMCW and FMICW waveforms using the back-projection (BP) [3] imaging algorithm. Wall reflections are the strongest contribution in the image when normal FMCW signals are used, whereas they are removed by the FMICW signals allowing the correct detection of the targets. For motion detection the target Doppler signature is extracted from the acquired data through double FFT processing and presented in Delay-Doppler patterns. Fig. 4 shows patterns for a person walking on two different trajectories behind the concrete wall when FMICW waveforms are used. In Fig. 4a the trajectory is radial, thus generating the highest Doppler shift (in this case approximately ± 20 Hz), whereas in Fig. 4b the trajectory is diagonal and as expected the value of Doppler is smaller (approximately ± 10 Hz).



Fig. 2 View of the experimental setup with stationary target on the open landing behind the brick wall

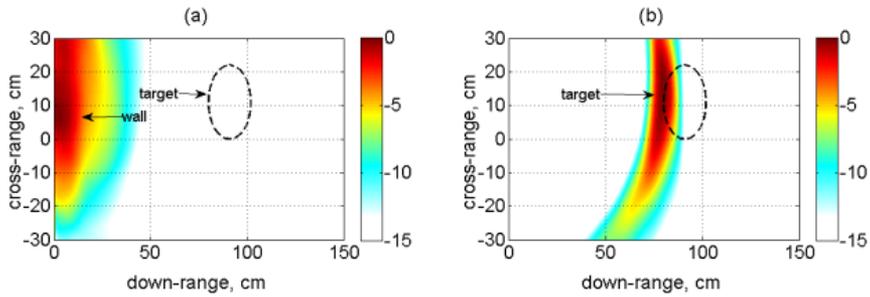


Fig. 3 Radar images for the cake tin behind brick wall: (a) using FMCW and BP algorithm, and (b) using FMICW and BP algorithm

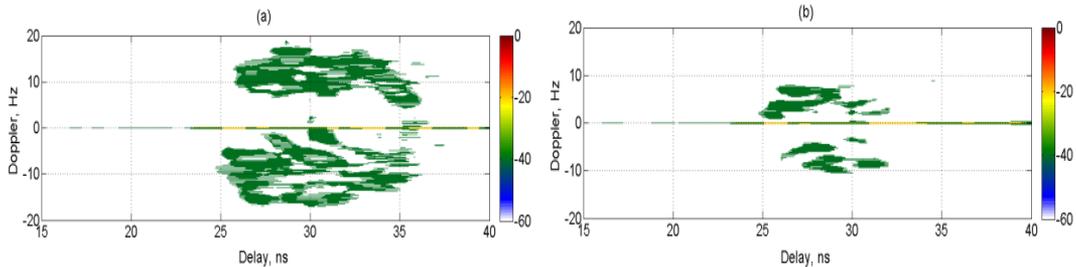


Fig. 4 Delay-Doppler for movement detection behind concrete wall using FMICW waveforms: (a) person walking on radial trajectory, and (b) person walking on diagonal trajectory

4 Experimental Validation for GPR applications

Experiments for the GPR have been performed using a $42 \times 50 \times 48$ cm plastic box filled with builder sand (with 7.5% of gravimetric water content), with different targets buried at different depth. Two Vivaldi antennas separated by 5.5 cm are used at the transmitter and at the receiver, and they are moved using an X-Y positioner along a synthetic array of 27 positions spaced by 1 cm to create an image of the volume under test. The system operates with a frequency range of 1.4 – 3.5 GHz. In Fig. 5 the target was placed 12 cm under the sand and the antennas were 10 cm above the sand. FMICW signal was generated with a gating sequence of 3 bits M-sequence with bit duration of 2.875 ns and delays τ_{rx1} and τ_{rx2} duration of 1.25 ns. Fig 6 shows that by using the FMICW we can remove the strong reflection from the air-ground interface thus being able to detect the target.

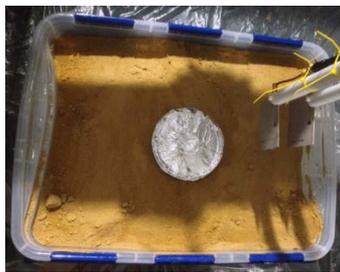


Fig.5 View of the Experimental GPR set-up

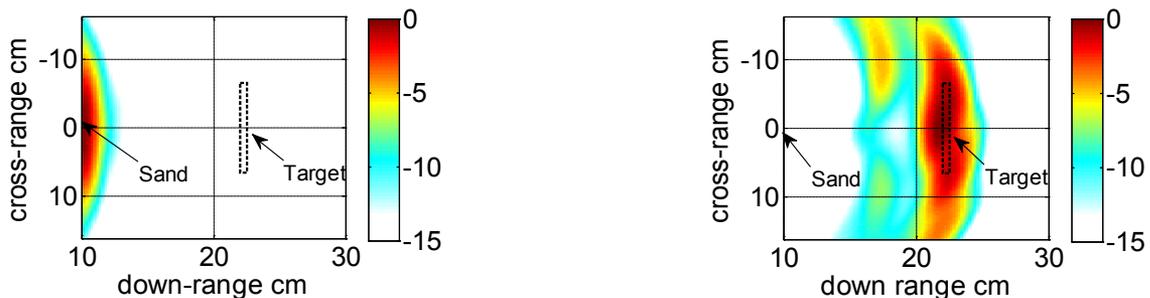


Fig.6 Radar Image of GPR, (left) using FMCW with BP algorithm, (right) using FMICW with BP algorithm

5 Experimental Validation for Breast Cancer Detection

Experiments were performed using a vector network analyzer (VNA) operating in the frequency range of 2-8.5 GHz. The VNA ports (A and B) were connected to the ports of two switches, which were in turn also connected to the transmitter and receiver antennas, which were separated by 4 cm. The switches were driven by two arbitrary waveform generators (AWG) used to generate the gating sequences. A rubidium clock was used to synchronize the devices. The phantom was made of 13 cm diameter plastic cylinder filled with vegetable oil, representing the fat tissue, and 1 cm diameter cylindrical tube filled with water, representing a tumor tissue. Measurements were performed in 36 positions around the phantom. Figure 7 shows the experimental set-up. The 7 bits M-sequence was used as gating sequence with bit duration of 750 ps. Fig 8 shows that by using the gating we can remove the strong reflection from the crosstalk thus being able to detect the target.

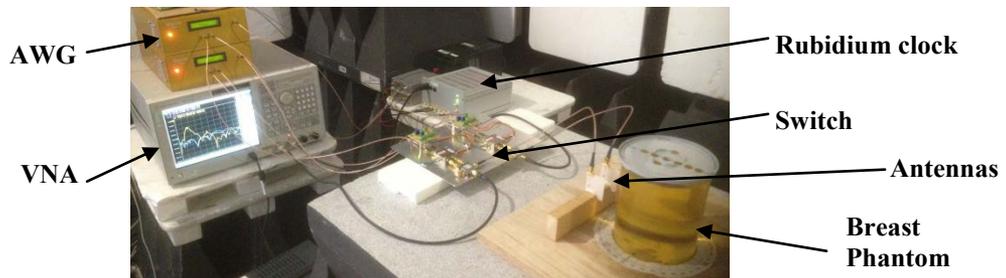


Fig.7 Radar Image of GPR, (left) using FMCW with BP algorithm, (right) using FMICW with BP algorithm

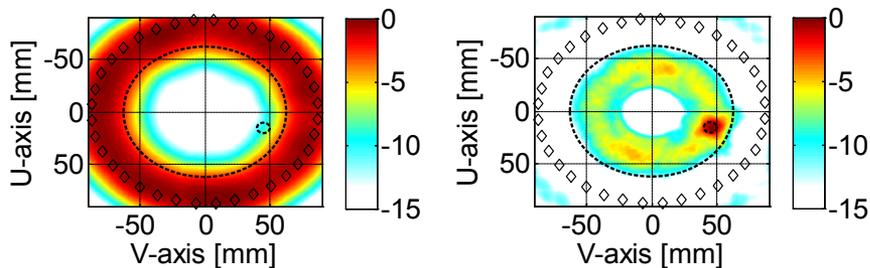


Fig.8 Radar Image, (left) using FMCW with BP algorithm, (right) using FMICW with BP algorithm

6. Conclusion

In this paper FMICW waveforms have been presented as a novel technique to mitigate/remove undesired reflections in radar imaging applications in the field of through-wall detection, GPR, and medical imaging. Further work could be carried out to improve the experimental setup and to combine FMICW with other post-processing techniques to enhance the overall performance of the radar system.

References

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