Real-time Through-wall Imaging Using SFCW Radar System

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Abstract

A swept frequency ultra wideband through wall radar (TWR) sensor operating in C-band is discussed in this paper. The sensor uses a Stepped-Frequency Continuous Wave (SFCW) waveform for ranging of targets. SFCW waveform processed by a digital receiver approximates UWB pulse in frequency domain. The paper brings out techniques involved in design of a TWR using SFCW signalling. Imaging of targets using back-projection algorithm is discussed. A real-time implementation of TWR target detection and imaging using an FPGA based multi-channel hardware platform for hand-held, battery operated TWR is described. Results achieved through realization of a prototype radar system are brought out for illustration.

I. INTRODUCTION

Urban battlefield situations which call for see Through Wall Radar (TWR) sensors for law-enforcement agencies to avert casualties and enable effective intervention. The ability to locate moving targets inside a building with a sensor situated outside the building would greatly improve situational awareness of the combat personnel. Such a sensor is expected to detect moving, as well as stationary objects inside the building, classify targets, and possibly provide inputs on the dimensions/geometry of the building. Information gathered by the radar should be rendered in human readable form such as 1-D (down range only), 2-D (down-range vs. cross-range) or 3-D (down-range vs. cross-range vs. height) with appreciable accuracy.

Operationally, the TWR design should cater for low power transmission (for low probability of interception), packaged for compactness, lesser weight, and it should be battery powered. Commercially built TWR units have also been reported to have features for remote control, monitoring and recording.

Through Wall Radar, with human target detection in perspective, offers a formidable design challenge that necessitates a sensitive, wide-band receiver, with synthetic aperture of spatially separated antennae for computing a multi-dimensional image of the illuminated scene. TWR designs have followed both time (impulse) and frequency domain (FMCW) waveform approaches. The SFCW radar technique offers substantial benefits over impulse radar systems. The main advantage of the stepped-frequency technique is that it is relatively easy with current technologies to efficiently sample SFCW signals with low speed analog-to-digital converters due to very low instantaneous bandwidth. Also, due to the transmission of long duration waveforms, a high average transmitted power is much easier to obtain than for short-pulse and impulse waveforms. Another advantage of stepped-frequency radar is its ability to skip over frequencies, which makes it jammer resistant. The disadvantage of the SFCW approach had been the acquisition time. As SFCW system has to step through a number of frequencies for an acquisition of one A-Scan and for each A-scan an IFFT has to be calculated. With today's technology which enables fast acting frequency synthesizers, and DSPs/FPGAs for signal processing, TWR design in frequency domain is becoming more popular.

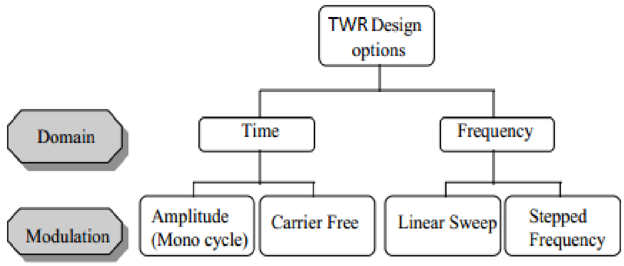

Figure 1. UWB TWR design options

The concept underlying seeing through opaque obstacles is similar to radar imaging. Specifically, when faced with a non-metallic wall, a fraction of the RF signal would traverse the wall, reflect off objects and humans, and come back imprinted with a signature of what is inside a closed room. By capturing these re-flections, we can image objects behind a wall. Building a device that can capture such reflections, however, is difficult because the signal power after traversing the wall twice (in and out of the room) is reduced by three to five orders of magnitude [3]. Even more challenging are the reflections from the wall itself (in stand-off mode of operation) or for that matter transmit to receive antenna mutual coupling, both of which result in much stronger signals in the receive chain than the reflections from objects inside the room [5]. Reflections off the wall overwhelm the receiver's Analog to Digital Converter

(ADC), preventing it from registering the minute variations due to reflections from objects behind the wall because of limited dynamic range. This behaviour is called the “Flash Effect" since it is analogous to how a mirror in front of a camera reflects the camera’s flash and prevents it from capturing objects in the scene. As the reflected echo signal from human body is extremely feeble, it is very important to devise mechanisms to counter the ‘flash’ phenomenon so that dynamic range of the receiver can be utilized effectively.

Since through-wall systems require, traversing the obstacle twice, the one-way attenuation doubles, leading to an 18-36 dB flash effect in typical indoor scenarios. This problem is exacerbated by two other parameters: First, the actual reflected signal is significantly weaker since it depends both on the

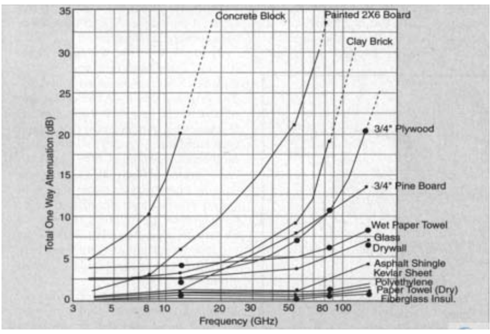

Figure 2. Illustrating through-wall EM attenuation[9]

coefficient as well as the cross-section of the object. The wall is typically much larger than the objects of interest, and has a higher reflection coefficient [5]. Second, in addition to the direct flash caused by reflections off the wall, through-wall systems have to eliminate the direct signal from the transmit to the receive antenna, which is significantly larger than the reflections of interest.

II SFCW RADAR

The phase of the received echo signal scattered from a target at range R relative to transmitted sinusoid is, $\varphi = \frac{4\pi FR}{c}$, where R is range to target, F is the transmitted frequency, c is the velocity of EM propagation. Evaluation of the first derivative of the above phase term provides insight into the value of phase information of the received signal.

$$\dot{\varphi} = \frac{4\pi F}{c}\dot{R} + \frac{4\pi R}{c}\dot{F}$$

The above equation illustrates the fact that received signal’s rate of phase change is a function of both derivatives of range, and frequency. Range rate phenomenon is used in estimation of target velocity in Doppler radars; whereas SFCW radars induce synthetic Doppler to echoes from stationary targets by changing transmit frequency at a uniform rate, and measuring the rate of change in phase in the received signal. Hence ranging of stationary objects is possible using SFCW. If the object is in motion, it generates a smear effect in the synthesized range profile. Techniques are available for estimating velocity of targets in SFCW signal processing chain.

1. SFCW processing

Stepped frequency CW radar incorporates an RF source or a direct digital synthesis (DDS) source, and DSP. The source is stepped between a start frequency, f_0 and a stop frequency, f_{N-1}, in equal, linear increments (Fig.3.). It is important to note that for swept FM-CW radar, the source is swept from f_{min} to f_{max} and linearly sampled on the fly. In either case, the radar is continuously transmitting. A return signal is formed by mixing the received signal with a portion of the transmitted one. This return signal is digitized at each step and stored. After each complete sweep of N steps, an inverse Fourier transform is performed to convert the data from the frequency domain to the time domain. This is the process of creating the synthesized pulse.

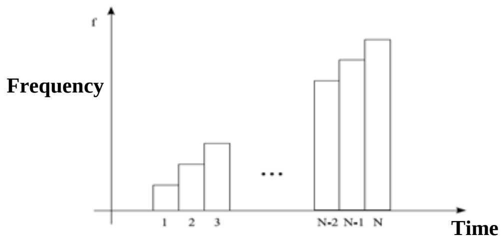

Figure 3. Transmitted signal frequency profile

Range information is based on the time-of-flight principle, which is a phase path difference measurement. Figure 4, illustrates the homodyne configuration of SFCW architecture.

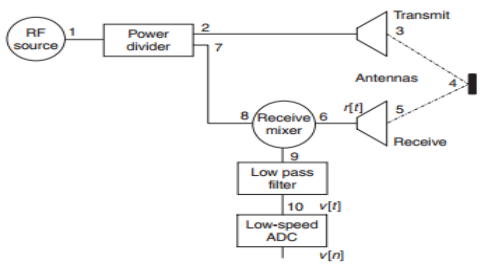

Figure 4. Homodyne Architecture for SFCW Processing

When the RF source is stepped in equal, linear increments of Δf from ($f_0, f_1, \ldots f_{N-1}$), the output voltages ($v[0]$, $v[1]$, $v[2]$,. . ., $v[N-1]$) sampled at each step resemble a sampled sinusoid:

$$v(n) = A\sum_{i=0}^{N-1}\delta(n-i)\cos(\varphi_i n)$$

where A and φ_i are amplitude and phase indices corresponding to the complex reflectivity coefficient of a target at i^{th} frequency, where $\varphi_i = 2\pi(f_i + n\Delta f)\tau_0$,$\tau_0$ is the delay corresponding to target range. Step size Δf determines the maximum unambiguous range, and resolution in down range is determined by bandwidth ($N\Delta f$).

At each step, *n*, one sample is collected is from the ADC, $v[n]$. The data from all *N* steps are then converted into the time domain pulse response equivalent with an Inverse Discrete Fourier Transform (IDFT). In case of multiple targets, the received signal can be modelled as a mixture of sine waves of different frequencies, as the rate of change of phase increases with range of the target. This is illustrated in Figure 5, where a total of ten targets at different range from the radar are simulated.

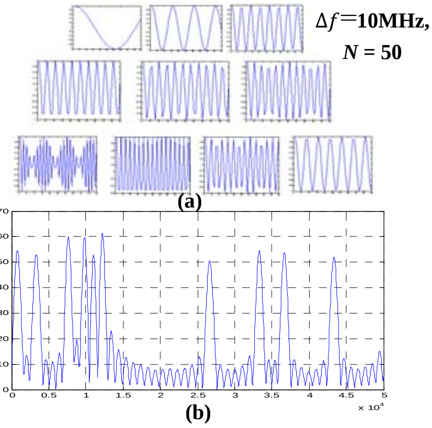

Figure 5. (a) Simulated SFCW baseband sampled echo from 10 scatterers and (b) composite range profile of targets

2 Imaging

Depiction of the illuminated scene as a 2-D picture was the objective of our TWR design. In an attempt to obtain a cross range resolution (locating targets in range and azimuth), a SAR technique called back projection was employed. This technique requires an array of antenna apertures to look at the targets. A uniform linear array of receiving elements was used for capturing echoes of targets through wall.

This class of algorithms contains the conventional SAR imaging (geometrical migration) as well as simple migration algorithms as diffraction summation [9]. The idea is to correlate data collected at each aperture position as a function of round-trip delay time. Backprojection coherently sums the sampled radar returns for each array element (pixel) of the image map. By the phrase coherent summation it is meant that the signal obtained at each aperture position is time-shifted to match, or align, it to a particular pixel element in the image map. Following this, the responses across all aperture positions are combined.

For illustration, consider the return from one target obtained at two radar positions $u_1$and u_2. Let us assume for simplicity, transmit and receive elements are collocated.

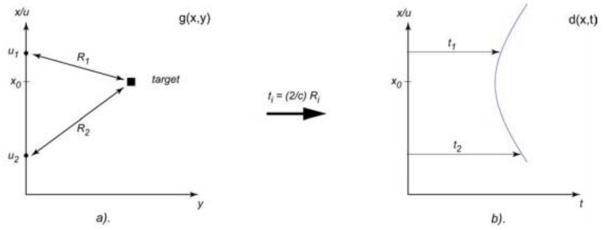

Figure 6. Transformation from object space to data space. Radar-to-target distance converted to round-trip return times.

Although *g*(*x, r*), the object space is illustrated, this is essentially unknown from the perspective of the collected radar data. What we have available for analysis is *d*(*x, t*), the reflectivity as a function of aperture position, the complex sample from IQ demodulator, and time delay. This is the data used to construct the image map *f*(*x, r*).

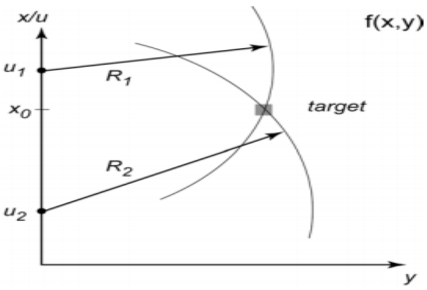

Figure 7. Construction of image map.

Since single radar receive antenna at position u_i cannot distinguish angle of arrival, the scattering centre could be located anywhere on a cylinder surrounding u_i, with radius $R_i = ct_i/2$, corresponding to time delay. A separate image map is constructed for each aperture position.

As successive images (corresponding to individual element positions) are added, points where the arcs overlap tend to reinforce while the other regions fade into background noise and shadowing. Coherent summation then, is simply an instance of constructive interference.

The figures 6(a) & 6(b) below depict simulation results of implementation of backprojection algorithm for the case of seven targets, obtained using a four element aperture, with collocated transmit and receive modules. The antenna array placed is along vertical edge of the figures.

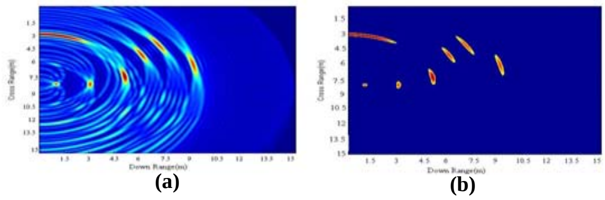

Figure 6. Results of backprojection algorithm (a) raw image (b) image after thresholding

III RADAR REALIZATION

A real-time implementation of the TWR operating in C-band was undertaken. Architecture of our radar is depicted in Figure 4. The SFCW signal with a bandwidth of greater than 500MHz was generated using a fractional-N PLL based synthesizer-VCO combination. The challenge was to achieve faster settling times in order to keep data acquisition time within reasonable limits. A four element (patch array) aperture was employed for data acquisition in a uniform linear array formation through an RF switch. This configuration requires only one receiver channel, and hence the antenna aperture can be scaled up with more elements for better cross range resolution. Power transmitted and receiver gain was optimized for avoiding saturation of components of the receiver.

A multi-channel, signal processing hardware unit with FPGA and DSP combination was designed to accomplish real-time 2-D imaging. An image update rate of 12 frames per second was achieved.

Figure 8. Multi-channel signal processing hardware

1. *Data acquisition*

A homodyne architecture based TWR receiver was used during initial experiments. A quadrature demodulator was selected for direct conversion of the received echo to base band. The resulting in-phase and quadrature signals were sampled with low-sampling rate ADC with 14 bit resolution. A common trigger between synthesizer and SP unit maintains time alignment between the data acquisition and the transmit pulse. For this alignment, the sample clock was generated using reference clock of the fractional-N PLL. The processor collects samples from the IQ demodulator at 1MHz rate, and forwards them to a pre-processor where de-noising of ADC samples is carried out. As the SFCW processor is interested in the composite reflectivity index of the echo at a particular step of frequency, only one sample is gathered after pre-processing for further processing per step. A heterodyne receiver, using two swept frequency synthesizers separated by an IF, and two passive mixers, was also experimented using the same hardware. Receiver sensitivity (CW) was found to have improved by at least 15dB due to band limiting IF filter used after mixer stages.

2. *Range profile computation*

Once the transmitter sweeps through bandwidth, complex reflectivity samples are padded with zeros. A 1024 point IFFT is computed by the FPGA using Altera^{R} Megacore^{R} function. The IFFT block is implemented in block floating point arithmetic. Magnitude part of the complex IFFT output represents range profile of the illuminated scenario. This process is continued for all the antenna elements in a round robin fashion (by switching to each Rx antenna pair using an RF switch). Range profiles computed from each antenna are fed to image former.

3. *Image former*

Backprojection algorithm was implemented in FPGA using pipelined external memory units. A concern with backprojection is the high computational (or algorithmic) complexity. For each pixel in an N x N array, one addition operation is required for each position of the aperture. Assuming there are N positions, this results in an $O(N^3)$ algorithm. This will have a significant impact on real-time operation of the system in terms of processor speed, data rates and buffering. The imaging routine computes a 1024 x 1024 pixel image projected image matrix in each cycle of transmission.

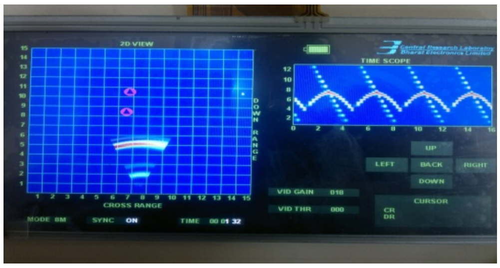

Figure 9. A view of TWR user display showing 2-D display (left) and time scope (right)

The pixels are coloured according to their strengths using a colour map for meaningful rendering. These pixels are written to a pair of memories in a ping-pong fashion. On an update event, every alternate frame from memory is resized to 360 x 360 pixels, and displayed on a VGA monitor by the SP hardware.

4. *Wall clutter removal using background subtraction*

Two methods of change detection are provided, coherent background subtraction and frame-to-frame change detection for removal of wall clutter. When using coherent background subtraction, raw data of the target scene is recorded and stored. The radar subtracts each new data set from the stored one displaying a coherent background subtracted image to the user thereby removing the source spectrum effects such as DC offset as well as non-moving background clutter. This method provides a coherent change detection mode where the target scene is subtracted from the original data set, showing all minute changes in the scene.

When using frame-to-frame change detection the radar subtracts the previous raw data set from the current one then displays the image of the difference. This provides a real-time moving target display, which shows anything that change (or moves) between frames and removes static radar clutter from the displayed image of the target scene. The subtracted frame may be taken from several frames in the past, which provides detection of slowly moving targets.

5. *Results*

Using FMCW radar range equation, a thermal-noise limited maximum range model was developed with design variables such as transmitted power, antenna gain, receiver gain etc. Wall attenuation was accounted for as loss factor. Actual wall attenuation was measured using two horn antennas on either sides of wall for estimating practical numbers for radar performance. Functional testing of TWR was conducted in free space for verifying detection range and cross ranging ability for multiple targets. TWR unit was then tested with different types of wall, with metallic, non-metallic, and human targets on the other sides of the wall. It was observed that the down range performance with metal objects like planar reflectors (10 x 10 sq. inch) was quite reasonable (in agreement with range calculations) with typical detection ranges of the order of 12m with antenna array close to the wall, where as cross range performance is not very good in comparison with free space. One possible justification for this could be that the wall profile was different across individual antenna elements, leading to non-uniform compensation in base band, and hence artefacts in the image.

It was observed that the receiver dynamic range was hampered by the mutual coupling when radar was operated close to the wall, and by wall reflections when operated in stand-off mode. The figures below depict actual screen shots of our TWR when a human target was walking away from a 9" solid concrete wall.

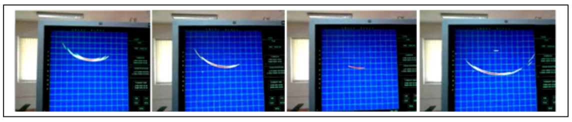

Figure 6. Screen shots of TWR display console showing human target echo rendered in 2-dimensions

CONCLUSION

An SFCW based TWR sensor capable of detecting, and imaging targets through non-metallic opaque barriers of up to 9" thickness has been discussed. It has been realized using fast acting synthesizers, and compact signal processing hardware. Algorithms for target detection, profiling, and imaging have been implemented in real-time, providing image updates at of 12 frames per second. A novel technique was developed for compensation of differential phase between reference mixer and echo channel mixer in case of heterodyne configuration. Major bottleneck which is hindering performance of TWR especially for detection of humans is 'flash' effect due to wall reflection and antenna cross-talk. Cross ranging of targets through wall is another challenge, as antenna interface to wall is different for each of the elements. Future work will focus on mitigation of flash effect using reflected power cancellation, and digital beam forming for better cross range resolution.

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