M-Sequence UWB Radar for Three Dimensional Through-the-wall Imaging

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***Abstract*—Ultra Wideband (UWB) technology shows a new way for Through-the-wall radar imaging which is of very high importance in urban warfare application. It has a great utilization especially for rescue and security operations. This paper makes use of M-Sequence signals which occupies UWB transmission bandwidth and is also having noise like waveform pattern. Modified back projection approach is used for three dimensional target imaging. The simulations results for a given environment of an object along with its comparison were presented.**

Keywords—***M-sequence, UWB radar system, through-the-wall Imaging, SAR scanning, three dimensional imaging***

I. INTRODUCTION

The terms Through-the-Wall Imaging (TWI), Through-the-Wall Radar Imaging (TWRI), Through Wall Surveillance (TWS) are synonymous for the basic objective of seeing through the non-metallic opaque materials and to retrieve information of the objects behind them. The term opaque is often used in optics and describes property of the materials that do not allow the light to pass through it. The other two terms of this class are: one which allows the light to pass through it and the other which partly allows the light to pass through it are called transparent and translucent materials respectively [1]-[3].

Through the wall imaging with UWB radar can be used e.g. to locate hostages or terrorists and weapons behind walls, people trapped in a building during fire, persons buried under fallen walls after earthquake, border controls for the detection of illegal immigrants, cigarettes in trucks, to reconstruct the interior of a room full of smoke during fire, etc. The key to a powerful UWB radar is the use of an appropriate stimulation signal because the whole device hardware and signal processing depends upon it [4][5].

In this paper, and the signal processing steps for feature extraction for through the wall imaging are also explained for M-sequence UWB Radar. The details of M-sequence are given in section 2. The reasons for using such signal as stimulus for UWB radar and the benefits of its usage are summarized in section 3. In section 4 architecture of M-sequence UWB radar is explained. Finally in section 5 the whole preprocessing and main processing algorithms are described. This paper is organized as follows: Section II describes the measurement scenario used for three dimensional imaging; Section III gives a note on the stimulus signal, Maximum- Length-Binary-Sequence (in short M-sequence) which occupies Ultra wide bandwidth. A mathematical formulation on three dimensional imaging is given in Section IV. Section V summarizes the simulation results and finally conclusions were drawn in Section VI.

II. MEASUREMENT SCENE

The measurement scene is same as that reported in [6] by the same authors. The simplified sketch is shown in fig 1. The radar system was horizontally scanned parallel to the front wall. The dimensions of the room are given as 10m×10m×10m which indicates the length, width and height of the room. Since the intention of the paper is to retrieve the three dimensional image of the target hidden behind the wall, for simplicity we assume that the wall attenuation is very less (approximately zero) and the delay is also zero. This assumption may not valid on the field. The assumption may show the shift in the position of the object.

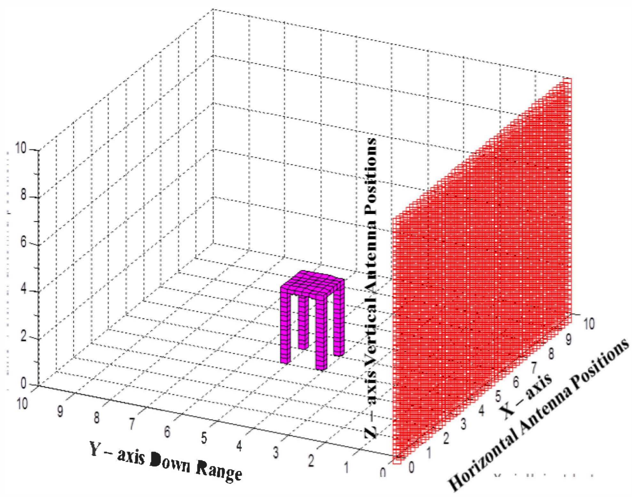

Figure 1: Orthographic View of the scenario

The stool behind the wall is considered to be as a target and is crafted by assuming that there exists a cube at a particular coordinate of 20cm length. By defining different coordinates whose contribution with the basic building block cube gives a structure like stool which is an object inside the

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room with height of 320cm and width of 120cm. It took 100 basic building blocks to represent the entire stool. The coordinates that we define here are later used for three dimensional reconstruction of an image. These coordinates are generally called scattering centres. In real time application identifying the scattering centre is a difficult task and demands for different methods for accurate estimation

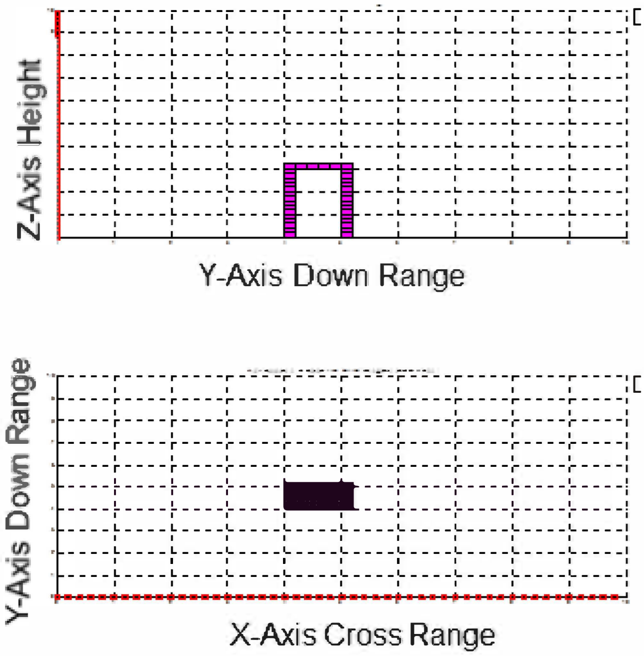

Figure 2: Side View and Top View of the scenario

III. M-SEQUENCE AND ITS BENEFITS

M-sequence is a special form of Pseudo-Random Binary Sequence (PRBS) which may be termed as one of the noise modulation techniques and has an attractive advantage of evenly spreading the radiated power throughout the spectrum thereby receiver is less susceptible to the interference [7],[8]. One of the major advantages of the noise like signals is its inherent immunity from jamming, detection and external interference. Moreover by using wideband noise waveforms one can achieve high resolution and reduced ambiguities in range and Doppler estimations. It also has high noise immunity, low probability of intercept (LPI), high electromagnetic compatibility, good electronic counter countermeasure (ECCM) capability; good counter electronic support measure (CESM) capability and ideal thumbtack ambiguity function.

PRBS signals ***x(t)*** are periodic and as such they are not really random but have the properties which are very close to those of real random signals. The PRBS signals consist of elementary impulses (chips), which are randomly distributed within a signal period. The autocorrelation function for ***x (t)*** is given by

$$R_{xx}(\tau) = \frac{1}{T}\int_T x(t)x(t+\tau)d\tau \tag{1}$$

A signal having a short autocorrelation function has a large bandwidth and thus it can in principle be used as a stimulus in high-resolution UWB radar. If the received signal caused from the backscattering of PRBS at a target is ***y (t)*** then the cross correlation function $R_{yx}(\tau)$ between stimulus and receive signal is given as

$$R_{yx}(\tau) = \frac{1}{T}\int_T y(t)x(t+\tau)d\tau \tag{2}$$

One must keep in mind that the information of interest is the impulse response function *h (t)* between the feed points of transmit and receive antennas. It includes the scattering behavior of the wall, targets and is embedded by the radiation behavior of the antennas. The impulse response function, autocorrelation and cross correlation functions are related by the convolution given below.

$$R_{yx}(\tau) = h(\tau) * R_{xx}(\tau) \tag{3}$$

But it is known that for any system with stimulus ***x(t)*** and the system response ***h(t)***, the output is given by ***y(t) = h(t) * x(t)***. Hence from Eq. (3)

$$R_{yx}(\tau) \approx h(\tau) \quad \text{for} \quad R_{xx}(\tau) = \delta(\tau) \tag{4}$$

i.e., ***δ (τ)*** is a Dirac delta function. Practically Eq. (4) means that the cross correlation function between the received and stimulus signals is proportional to the impulse response function as long as the autocorrelation function of the stimulus is narrow compared to the impulse response of the device under test (here the impulse response function ***h(t)*** between the feed points of the transmit and receive antennas) In frequency domain, Eq. (4) requires a bandwidth of the stimulus exceeding that of the device under test.

For understanding of how M-sequence looks and what are its properties, consider 3 shift stages. The number of chips generated is given by

$$n_1 = 2^N - 1 \tag{5}$$

Where n_1 represents the number of chips and N is the number of generator shift stages. So for N=9 the M-sequence will have 511 chips per period T. The M-sequence generator for N=9 is shown in Figure 3.

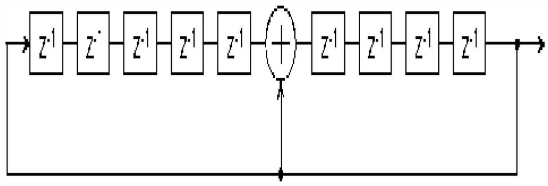

Figure 3: M-sequence generator with 9 shift registers

It can be seen from Figure 3 that only 2 feedback connections and one summation are needed for implementation. For illustration one period of 511 chips length M-sequence is shown in Figure 4, and the same but delayed (346 chips) and noise corrupted M-sequence with 6dB SNR is depicted in Figure 5. The output after correlation of the two signals Figure 3 and Figure 4 is shown in Figure 5. From the noised signal of Figure 5 one can easily obtain the information about delay because of the high correlation gain of M-sequence that is equal to $2^N - 1$.

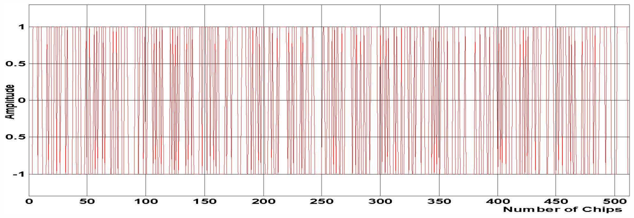

Figure 4: M-sequence generator with 9 shift registers

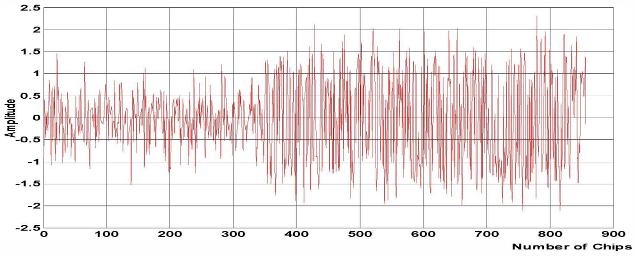

Figure 5: Delayed and noise corrupted (6 dB) M-sequence

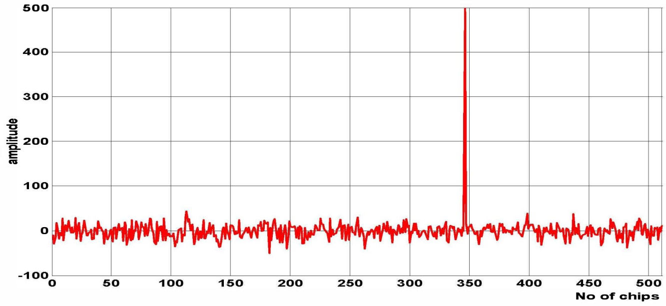

Figure 6: Correlation of fig 4 and fig 5

Benefits of using M-sequence:

Besides the high correlation gain as explained above, M-sequences have following advantages in UWB radar applications.

- They can easily be generated up to tenths of GHz of bandwidth by a digital shift register which is clocked by stable oscillator.
- The method permits monolithic integration of the RF-electronics in SiGe-technology.
- Since they are periodic it is possible to apply cost effective sub-sampling methods for signal recording and to avoid a spectral bias error.
- They have a low crest factor. Low crest factor signals distribute their energy uniformly over the time. This maximizes signal energy even at low peak voltages and also maximizes the SNR.
- They are characterized by small binary voltage amplitudes that allow extremely fast digital switching in integrated circuit technology. It satisfies the demanding requirements on bandwidth and low jitter.
- They allow the real-time operations because of their high measurement speed.

IV. Three Dimensional Imaging

Lending the concept from the back projection algorithm a novel algorithm is proposed for three dimensional imaging that enhances the target information (This is same as that reported in [6]). Necessary equations, algorithm steps and its implementation for three dimensional imaging in this section are developed. The algorithm retrieves the image of the scanned area by making use of the A-scan signals at different receiver positions. Since the image is of 3D and is represented by an L×M×N matrix, the aim is to obtain the corresponding numerical values to fill the matrix, such that the formed image represents the scanned scene. Each numerical value in the L×M×N matrix represents a voxel (VOLumepiXEL) value of an image.

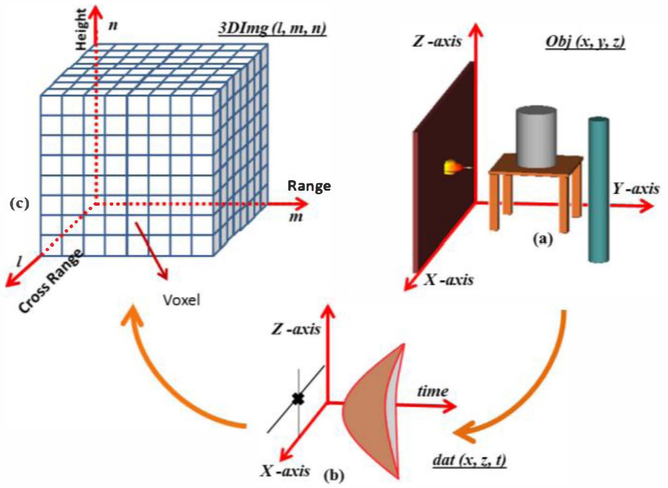

Figure 6: Three Dimensional Imaging (a) Object Space (b) Data Space (c) 3D Image Space

In the process of correlating the collected data at each platform position as a function of round-trip delay three different coordinate systems are defined similar to that in 2D imaging. An object space, data space and 3D image space for three dimensional imaging is picturized in Figure 6.

The received echoes at different receiver positions are used to map object space to data space. Data space is the function of platform position (cross range, height) and time, ***dat (x,z,t)***. Multiple curved surfaces are formed in the data space, an example with specified transceiver position is shown in Figure 6 (b). Each curve in the data space represents three dimensional PSR. The 3D image is represented by 3D matrix of order L×M×N. This matrix is filled with numerical values based on the echoes.

A-scan signal received at each receiver position assuming N targets in the scanned region is given by

$$A_{ij}(t) = \sum_{k=1}^{N} a_{ijk} s(t - t_{ijk}) \tag{6}$$

Where

$A_{ij}(t)$: Received A-scan signal at (i, j) platform position, $i = 0, 1, 2, \ldots\ldots P$; $j = 0, 1\ 2, 3\ldots. Q$.

a_{ijk}: Reflection coefficient of k^{th} target when transceiver is at (i, j)

t_{ijk}: delay of the signal from (i, j) transceiver position to k^{th} target position and back to (i, j) transceiver position.

The expression for the delay is given by

$$t_{ijk} = \frac{2R_{ijk}}{c} \tag{7}$$

3D PSR represents the spreading of signal energy in three dimensional spaces. For a given A-scan signal the PSR is given by

$$f_p(x_i, y_j, z_k) = A_p(t - \tau(x_i, y_j, z_k)) \tag{8}$$

Where $f_p(x_i, y_j, z_k)$ represents the volume map as a function of voxel coordinate (x_i, y_j, z_k). $i = 0, 1, 2, 3\ldots. L$; $j = 0, 1, 2, 3\ldots\ldots M$; $k = 0, 1, 2, 3\ldots\ldots N$; $\tau(x_i, y_j, z_k)$ is the focusing delay. The 3D PSR at (9.8, 9.8) transceiver position is indicated in Figure 7. It is observed that there exists multiple curves with different ranges indicating multiple target points.

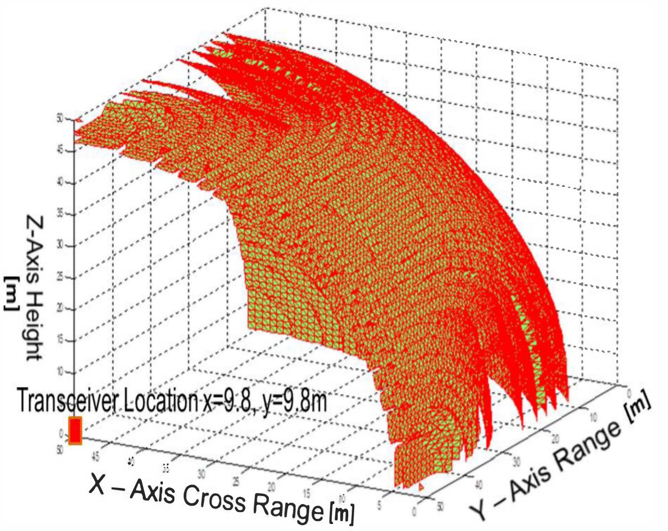

Figure 7: Three Dimensional Point Spread Response

By collecting 3D PSR's at all transceiver locations, the 3D image is obtained from the equation

$$B(x_i, y_j, z_k) = \sum_{p=1}^{P} f_p(x_i, y_j, z_k) \tag{9}$$

Where p varies from 1 to P, indicates the platform position defined for both vertical and horizontal motion.

V. Results

Three-dimensional imaging using M-sequence with 9 shift registers and 511 chips is done and the results are shown in Figure 8, 9 &10. Out of 100 voxels of the actual target only 7 are recovered in the final 3D image. This indicates that the accuracy of the final 3D image gets worse compared to the impulse based signals. But as explained in section III, the hardware implementation of the system is easy compared to the impulse based systems.

VI. Conclusions

This paper uses M-sequence signal with 9 shift registers and 511 chips sequence length as input signal for through-the-wall imaging application using UWB Radar. As per the results obtained it is observed that only 7% of the voxels are of the original target. Compared with UWB Impulse radar [6], [9] this is far less.

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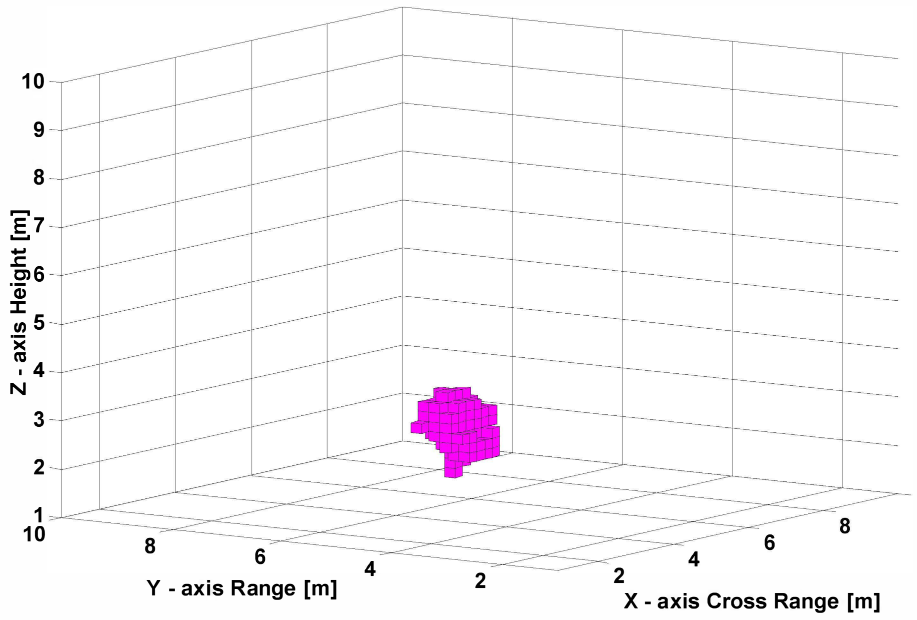

Figure 8: Orthographic view of the target after 3D imaging using M-sequence

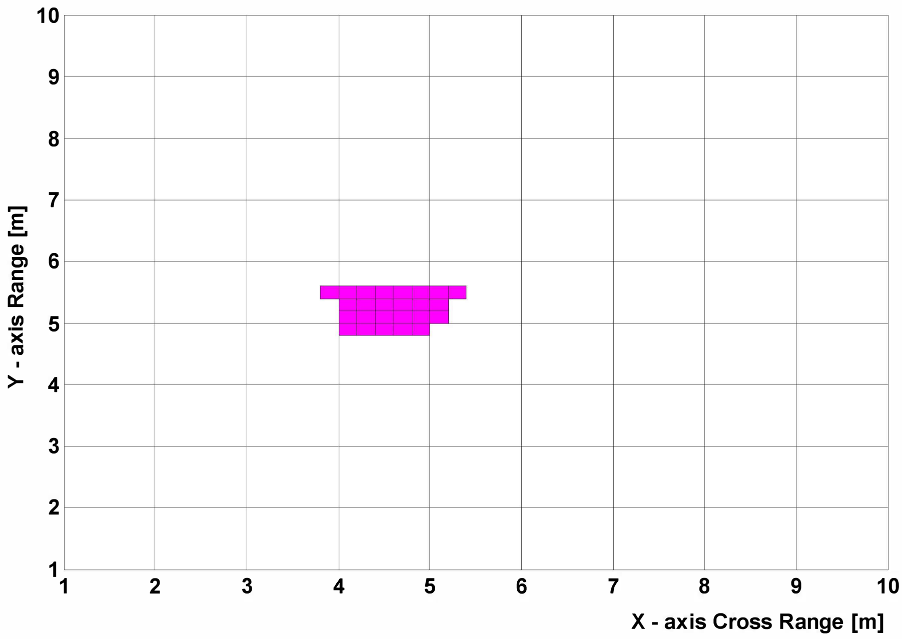

Figure 9: Top-view of the target after 3D imaging using M-sequence

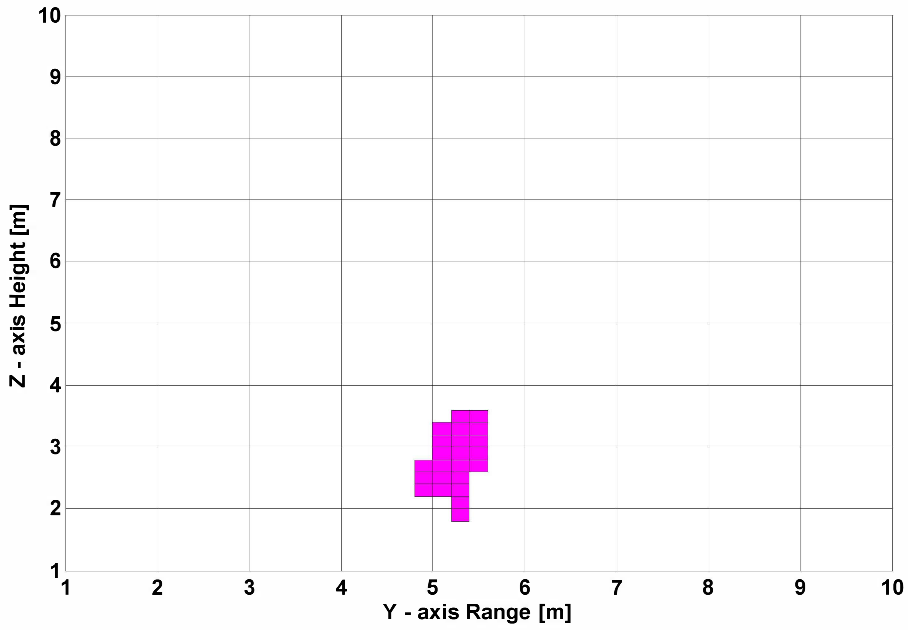

Figure 10: Side view of the target after 3D imaging using M-sequence