Frequency Domain Clutter Removal for Compressive OFDM Ground Penetrating Radar

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Introduction

- **Ground penetrating radar (GPR)**
  - Sensory system for non-destructive evaluation of transportation infrastructure.

- **High operation efficiency is one critical specification for GPR system design.**
  - Highway driving speed: 60 mph
  - Good data spacing: 1 cm
  - Therefore, pulse repetition frequency: 30 kHz

- **Two Issues:**
  - How to leverage sensing efficiency
  - How to reduce data volume
Introduction

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- **Two Issues & Existing Solution:**
  - How to leverage sensing efficiency - *Orthogonal frequency-division multiplexing (OFDM)*
  - How to reduce data volume - *Compressive sensing (CS)*
Compressive OFDM GPR Sensing

Reduce the required number of tones for signal synthesis

Multi-tone signal radiation and receiving

Compressive OFDM GPR Sensing

Reduce the required number of tones for signal synthesis

Multi-tone signal radiation and receiving
OFDM Signal Generation

- OFDM signals contain many sub-carriers that are orthogonal among each other eliminating the inter-carrier interference.
- Quadrature Phased Shift Keying (QPSK) for OFDM spectrum generation.
- When the total signal duration equals $N/f_a$, orthogonality among different tones can be achieved.
- Inverse Discrete Fourier Transform (IDFT) for OFDM signal generation.

Compressive Sensing

\[ y = \Phi \Psi x \]

\[ y = \Phi X = \Phi \Psi x \]

\[ M \times 1 \]
Measurements

\[ M \times N \]
Measure Matrix

\[ K < M \ll N \]

\[ N \times 1 \]
Sparse Signal

\[ K \text{ nonzero entries} \]

\[ N \times N \]
Sparsify Matrix

Compressive OFDM GPR Sensing

\[ y = \Phi X + \eta = \Phi \Psi x + \eta = Ax + \eta \]

\( \eta \in \mathbb{R}^M \) -- measurement noise
Solution and Criterion

• As long as $\Phi$ and $\Psi$ are incoherent, sparse vector $\mathbf{x}$ can be reconstructed by solving the $L1$-minimization:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}'} ||\mathbf{x}'||_1, \text{ s.t. } ||\mathbf{y} - A\mathbf{x}'|| \leq \varepsilon$$

$\varepsilon$ bounds the amount of noise in the data.

• The applicable value of $M$ is determined by:

$$M \geq C_0 \cdot \mu^2(\Phi, \Psi) \cdot K \cdot \log N$$

$C_0 > 0$ is a constant; coherence $\mu(\Phi, \Psi)$ measures the largest correlation between $\Phi$ and $\Psi$. When $\Phi$ and $\Psi$ are incoherent, $\mu(\Phi, \Psi) = 1$.

• A small $K$ for the time domain object signal ensures accurate reconstruction with less number of frequency tones in compressive OFDM GPR

Sparsity of GPR Signal in Time Domain

\[ x(t) = s(t) + g(t) \]

- \( K_x \) non-zero elements in \( x(t) \) and \( K_s \) non-zero elements in \( s(t) \).
Sparsity of GPR Signal in Time Domain

\[ x(t) = s(t) + g(t) \]

- \( K_x \) non-zero elements in \( x(t) \) and \( K_s \) non-zero elements in \( s(t) \).
- \( K_x \gg K_s \)

Clutter is the unwanted echoes in radar system, typically generated by ground surface reflection.
Number of Essential Frequency Tones

Time Domain

\[ x(t) = s(t) + g(t) \]

\( N \) frequency tones \( w_i, i = 1, 2, 3, \ldots, N \)

Frequency Domain

\[ X(w_i) = S(w_i) + G(w_i) \]

OFDM GPR Sensing

- GPR Signal
- Target Signal
- Ground Clutter
Number of Essential Frequency Tones

\[ K_x \gg K_s \quad \Rightarrow \quad M_{x_{\text{min}}} \gg M_{s_{\text{min}}} \]

- Less frequency tones are needed for reconstructing \( s(t) \) in comparison with reconstructing \( x(t) \).
Clutter Removal in Frequency Domain

- **Less frequency tones are needed** for reconstructing $s(t)$ in comparison with reconstructing $x(t)$.

- **Therefore, applying clutter removal on compressed frequency measurement data to remove $G(w_i)$ facilitates $s(t)$ signal recovery.**
Clutter Removal Model

- **Calibration**: synthesize an A-Scan trace $x_0(t)$ using the compressed OFDM signal to scan a position with no objects under test.

- Ground surface reflection signal $g_0(t)$ is extracted as reference.

- In time domain, due to linear property, the varying ground surface conditions will only cause magnitude variation and time delay in GPR ground surface reflection.

- Therefore, the ground reflection in other A-Scan waveforms can be represent as the delayed and scaled version of $g_0(t)$:

$$g(t) = \alpha g_0(t - \tau)$$

$\alpha$ - amplitude scale coefficient; $\tau$ - time delay.

- The spectrum of $g(t)$ is

$$G(w_i) = \alpha G_0(w_i)e^{jw_i\tau}$$

$\alpha$ - amplitude scale; $w_i\tau$ - phase shift.

Solving $G(w_i)$ and Extracting $S(w_i)$

- To solve $\alpha$ and $\tau$, the nonlinear least squares criterion is applied

$$[\hat{\alpha}, \hat{\tau}] = \arg \min_{\alpha, \tau} \sum_{i=1}^{N} |X(w_i) - \alpha G_0(w_i)e^{jw_i\tau}|^2$$

- $\hat{\alpha}$ and $\hat{\tau}$ can be analytically solved as

$$\hat{\tau} = \arg \max_{\tau} \left| \sum_{i=1}^{N} X(w_i)G_0^*(w_i)e^{-jw_i\tau} \right|$$

$$\hat{\alpha} = \frac{\sum_{i=1}^{N} X(w_i)G_0^*(w_i)e^{-jw_i\hat{\tau}}}{\sum_{i=1}^{N}|G_0(w_i)|^2}$$

- Then, $G(w_i)$ is subtracted from the measurement frequency response data set $X(w_i)$ to obtain the target signal spectrum $S(w_i)$.

- A higher compression ratio can thus be achieved when CS reconstruction is performed on $S(w_i)$ instead of on $X(w_i)$.

Experimental Results: Configuration

- GPR data collected from scanning a 1.8 meters long concrete walkway where six reinforcing bars are buried underneath.
- A-Scan traces collected at every 0.48 mm
- Data acquisition time window: 10 ns.
- The data matrix size: 288*380.
- OFDM signal bandwidth: 2 GHz to synthesize a 500 ps wide pulse.
- For uncompressed OFDM GPR signal generation, $N = 2048$ frequency tones are generated and radiated.
- While for the compressive OFDM implementation, $M = 2048 * p \ (0 < p < 1)$ frequency tones are randomly selected. (the sensing accuracy increases when $M$ or $p$ increases)

GPR A-Scan Trace Analysis

Reconstructed A-Scan trace with $p = 20\%$ (A buried Rebar)

Compressed Frequency Spectrum

Recovered A-Scan without Clutter Removal

Recovered A-Scan with Clutter Removal
GPR A-Scan Trace Analysis

- Signal-to-Error Ratio (SER) evaluates the discrepancy between the reconstructed signal and the true object signal.
- Let \( x \) be the A-Scan traces recovered from the compressive OFDM frequency measurements, and \( x_0 \) be the A-Scan traces calculated from the full OFDM frequency spectrum without compression.

\[
SER = 20 \log_{10} \frac{\|x\|_2}{\|x - x_0\|_2}
\]

where \( \|*\|_2 \) is the \( l_2 \)-norm operator.

Reference object pulse with full spectrum measurements

SER values for different \( p \)
GPR B-Scan Image Analysis

Clutter removal coupled compressive OFDM GPR reconstructed B-Scan with various $p$

6 rebar buried in the concrete walkway

$p = 100\%$

$p = 60\%$

$p = 30\%$

$p = 5\%$
GPR B-Scan Image Analysis

Signal-to-Clutter ratio (SCR) characterizes the power ratio of backscattering signal from the targets under test and from the ground surface reflection.

SCR under various values of $p$ for compressive OFDM GPR with and without Clutter Removal
Conclusions

- A frequency domain clutter removal method is developed to eliminate the ground surface reflection for compressive OFDM GPR sensory system.

- This method reduces the GPR data volume by utilizing fewer sensing frequency tones while not compromising the sensing accuracy.

- The experiments demonstrate that the compressive OFDM GPR sensory system employing frequency domain clutter removal can effectively accomplish high sensing accuracy and high compression ratio.
References & Acknowledgement

Core References:


More References and publications on the website:
http://www.uvm.edu/~yzhang19/publications.html

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Thank You!

Questions, please?