A Compressive Sensing Based Approach for Through-Wall Tracking of Moving Targets

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Outline

• Objective

• Background
  – Compressive Sensing (CS)
  – Our previous work: CS-based Joint DoA-Range Processing

• CS-based Through-Wall Tracking Approach

• Human Walking and Scattering Model

• Simulation Results
  – Spherical Targets
  – Human Target

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Objective

• A capability to track moving targets through-wall is important in many applications, e.g. disaster rescue service, health monitoring, security, military, ...

• Popular approaches: impulse ultra-wide band (UWB) radar, stepped-frequency continuous wave (SFCW) radar

• SFCW radar: high reliability, stability, and relatively easy implementation.

• Propose: a CS-based SFCW framework for through-wall tracking of moving targets
Why Compressive Sensing?

- **Challenge:** high quality images at a fast speed
  - High range resolution - wide bandwidth
  - High cross-range resolution - large number of ant. elements
  - Long data acquisition time → not suitable for real-time detection and tracking

- **Sparse target space ⇒ Compressive Sensing (CS):**
  - recover the sparse signal from fewer measurements in the presence of noise

- **CS applied to TWRI:**
  - propagation delay through a single layer wall using Snell’s law
  - multilayered wall based on the far field layered medium Green's function

Overview of Compressive Sensing

• Replace conventional samples with \textit{fewer linear projections} $y = \Phi x$
  – When $x$ is sparse/compressible
  – Projection $\Phi$ \textbf{not full rank} ($M < N$) $\rightarrow$ lose information in general
  – \textit{Restricted Isometry Property (RIP)}

\begin{align*}
y & = \Phi x \\
M \times 1 & \quad \text{measurements} \\
N \times 1 & \quad \text{sparse signal} \\
K < M & = O(K \log N) \ll N \\
& \quad \text{i.i.d. Gaussian} \\
& \quad \text{partial Fourier} \\
& \quad \text{...}
\end{align*}
Joint Array and Doppler Processing

- Tracking:
  - Spatial beamforming
  - Ranging: inverse FFT
    - stepped frequencies: $M$ frequencies, $f_1$ to $f_M$ (centered at $f_c$), frequency step $\Delta f$
  - Doppler processing (using Short-time Fourier Transform - STFT)

Joint Array and Doppler Processing

\[ S(\theta_i, R_l, t) = \frac{1}{N} \sum_{m=1}^{M} \left( \sum_{n=1}^{N} E_s(y_n, f_m, t) e^{-j(n-1)2\pi d f_m c \sin \theta_i} \right) e^{j2\pi f_m \frac{2R_l}{c}} \]

\[ \zeta(f_D, \theta_i, R_l, t) = \int_{t'} S(\theta_i, R_l, t') h(t'-t) e^{-j2\pi f_D t'} dt' \]

- stepped frequencies \( M \) frequencies: \( f_1 \) to \( f_M \) (centered at \( f_c \)), frequency step \( \Delta f \)
- \( N \): number of antennas
- \( d \): inter-element spacing
- \( \theta \): scanning angle
- \( r \): range
- \( f_D \): Doppler frequency
- \( h(t) \): time window
Previous Work: CS-based Joint DoA-Range Processing

- Linear model between measured signals and the joint DoA-range space:

\[
E_s(y_n, f_m, t) = \sum_{l=1}^{M} \sum_{i=1}^{P} S(R_l, \theta_i, t) e^{j(n-1)2\pi d\frac{f_m}{c}\sin\theta} - j2\pi f_m \frac{2R_l}{c}
\]

- Measured signal
  - \(N\) receiver positions
  - \(M\) frequencies

- Target space
  - spatially sampled

Current Work: CS-based TW Joint DoA-Range Processing

- New linear model between the joint DoA-range space and measured signals needs to be built
- Wall effect compensation: transmission coefficients
CS-based Joint DoA-Range Processing with Compensation of Wall Effect

- New linear model between the joint DoA-range space and measured signals:

$$E_s(y_n, f_m, t) = \sum_{i=1}^{M} \sum_{l=1}^{P} S(R_l, \theta_i, t) T_{h-a}(y_n, r, f_m) T_{a-h}(r, y_i, f_m)$$

$$\zeta(f_d, \theta_i, R_h, t)$$

 Measured signal
- $N$ receiver positions
- $M$ frequencies

Target space
- spatially sampled
### Measurement Matrix Construction

\[
E_s(y_n, f_m, t) = \sum_{l=1}^{M} \sum_{i=1}^{P} S(R_l, \theta_i, t) T_{h-a}(y_n, r, f_m) T_{a-h}(r, y_t, f_m) e^{j(n-1)\frac{2\pi f_m}{c} \sin \theta_i - j2\pi f_m \frac{2R_i}{c}}
\]

Rewrite in the matrix form:

\[
E_s = \begin{bmatrix}
\Phi & \Psi
\end{bmatrix} \begin{bmatrix}
S
\end{bmatrix}
\]

- \(M\): the number of frequencies
- \(N\): the number of receivers
- \(P\): the number of angles of arrival

The \((m-1)N+n, (l-1)P+i\)\textsuperscript{th} element of \(\Phi\)

\[
\phi_{(m-1)N+n,(l-1)P+i} = T_{h-a}(y_n, r, f_m) T_{a-h}(r, y_t, f_m) e^{j(n-1)\frac{2\pi f_m}{c} \sin \theta_i - j2\pi f_m \frac{2R_i}{c}}
\]
Measurement Schemes

- Conventional method: measures $MN$ samples ($M$ frequencies, $N$ receivers)
- CS method: measures $M^{\text{CS}}(<M)$ random frequencies at each antenna element
  $\rightarrow$ reduces the data acquisition time by a factor of $M / M^{\text{CS}}$
Conventional Measurement Matrix

\[ E_s = \Phi \Psi S \]

**Measurement Matrix**

\[ E_s = \Phi \]

\[ \Psi \]

\[ S \]
CS Measurement Matrix

\[
E_s^{CS} = \Phi^{CS} \Psi S
\]

\(E_s^{CS}\): reduced data set for CS, \(NM^{CS}\) selected samples out of \(NM\) possible data set
\(\Phi^{CS}\): randomly selecting \(NM^{CS}\) rows from \(\Phi\)
Signal Reconstruction

- Achieve sparse reconstruction of the DoA-range space using a reduced set of measurements
- Scene reconstruction using $l_1$-minimization
  \[
  \hat{\mathbf{S}} = \arg \min_{\mathbf{S}} \| \mathbf{S} \|_1 \text{ subject to } \| \mathbf{E}_s^{\text{CS}} - \Phi^{\text{CS}} \Psi S \|_2 \leq \delta
  \]
  - $\delta(>0)$ provides noise robustness
- Convex optimizations
- Greedy algorithms:
  - Orthogonal Matching Pursuit (OMP), stagewise OMP (StOMP)
  - Compressive Sampling Matching Pursuit (CoSaMP)
  - ...
Human Walking Model

- Human walking motion is based on Boulic model.

Human body parts are modelled by using ellipsoids between 16 joints.

Ozlem Kilic, Jose M. Garcia-Rubia, Nghia Tran, Vinh Dang, and Quang Nguyen, "Tracking of moving human micro-Doppler signature in forest environments with swaying tree components by wind", Radio Science, 2015 (accepted)
Human Scattering Model

- Human body parts are modelled by using ellipsoids between 16 joints.
- In this model, a full-wave technique, Method of Moments (MoMs) enhanced by Fast Multipole Method (FMM), is implemented on GPU cluster.

Ozlem Kilic, Jose M. Garcia-Rubia, Nghia Tran, Vinh Dang, and Quang Nguyen, “Detection of moving human micro-Doppler signature in forest environments with swaying tree components by wind”, Radio Science, 2015 (accepted)
Through-Wall Human Scattering Model

• Plane-wave spectrum approach (Angular spectrum method):

Procedure:

1. Calculating the complex scattered field over a sampling grid (using hardware-accelerated FMM)
2. Taking the 2D-IDFT to decompose into infinite series of component plane waves
3. Multiplying each point in the 2D-IDFT by propagation terms (incl. transmission coefficient)
4. Taking the 2D-DFT to yield the reconstructed field on the destination plane
Plane-wave Spectrum Approach

• Plane-wave decomposition (step 1 and 2)

\[
F_x(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_x(x, y, z = 0) e^{j(k_xx + k_yy)} \, dx \, dy
\]

\[
F_y(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_y(x, y, z = 0) e^{j(k_xx + k_yy)} \, dx \, dy
\]

• Field reconstruction at the destination plane (step 3 and 4)

\[
\tilde{E}(\vec{r}) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ F_x(k_x, k_y) \hat{x} + F_y(k_x, k_y) \hat{y} - \left[ \frac{k_x}{k_z} \right] F_x(k_x, k_y) \\
+ \left[ \frac{k_y}{k_z} \right] F_y(k_x, k_y) \right\} \hat{z} \left\{ T(k_x, k_y) e^{-j(k_zz)} - j(k_xx + k_yy) \right\} \, dk_x \, dk_y
\]
Simulation Results - Spherical Targets

- Simulation setup:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c$</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>800MHz</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>10MHz</td>
</tr>
<tr>
<td>Number of frequencies</td>
<td>81</td>
</tr>
<tr>
<td>Range resolution</td>
<td>18.7cm</td>
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<tr>
<td>Maximum unambiguous range</td>
<td>15m</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>27</td>
</tr>
<tr>
<td>Antenna inter-spacing</td>
<td>6.25cm</td>
</tr>
<tr>
<td>Wall relative permittivity</td>
<td>6.5</td>
</tr>
<tr>
<td>Wall loss tangent</td>
<td>0.011</td>
</tr>
<tr>
<td>Sphere radius</td>
<td>0.1m</td>
</tr>
</tbody>
</table>

- Conventional method: $S = 81 \times 27 = 2187$ measurements
- Compressive Sensing based method: $S = 10\% \times 81 \times 27 = 216$ measurements
Simulation Results - Spherical Targets

CS-based imaging with wall compensation at $t_{37} = 89\text{ms}$

CS-based imaging w/o wall compensation

Conventional method with wall compensation (full meas.)

CS-based tracking results (with wall compensation) (256 time instants = 634ms)
Simulation Results - Human Target

• Tracking results over 3 walking cycles of human motion
Conclusions

• A CS-based tracking approach of moving targets behind the wall in the joint DoA-range space for the SFCW radar is proposed
• The transmission coefficients are integrated to take into account the wall effects.
• The approach can be extended to multi-layered wall
• Multiple targets can be resolved using fewer number of randomly selected measurements
• Future investigations:
  – different CS reconstruction algorithms
  – different types of human motions
  – CS-based algorithm for DoA-range-Doppler space
Thank you for listening