Through Wall Imaging Based on MIMO UWB Radar With a Fast Image Reconstruction Method

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What is Ultra Wideband?

Percentage bandwidth:

$$B = \frac{2(f_H - f_L)}{(f_H + f_L)}$$

Signal classification \textit{wrt.} bandwidth:

- Narrowband : \( B < 0.01 \)
- Wideband : \( 0.01 < B < 0.25 \)
- Ultra Wideband : \( B > 0.25 \)

Ultra Wideband Signals:

- Square wave and triangle wave
- Chirp
- Impulse
Impulse Radio Ultra Wideband

• Impulse radio uses impulse signal is the most popular UWB signal
• Between impulse radio signals, Gauss waveform and its derivatives are the widely used waveforms

Unique properties of UWB signals are:
• Fine range resolution
• Foliage and ground penetration
• Low probability of intercept
• Non-interfering waveform

In addition;
• UWB signals are more meaningfully affected by the target than narrowband signals
• They are easily analyzed to extract information about the target shape and its materials
Ultra Wideband Radar

The potential advantages of using UWB waveforms for Radar are:

• Better spatial resolution
• Detectable materials penetration
• Easier target information recovery from reflected signals
• Lower probability of intercept signals than with narrowband signals
• Non-interfering signal properties
• Time domain processing

Thus, UWB radar offers:

• Covert operation
• Target imaging and discrimination
• Frequency spectrum sharing with other Radar and communications systems

Also, it radiates and consumes very little power.
Basic Short Range Impulse Radar

- Pulse generator generates pulses with very short duration
- These pulses are reflected by the target
- Due to external interference and thermal noise, received signal is noisy.
- Receiver samples the reflected signals and signal processing block starts to process
UWB Radar Applications

Through the wall imaging

Ground Penetrating Radar

Medical imaging (respiratory motion)

Collision avoidance
Real-Time Through The Wall Imaging using MIMO UWB Radar

• In this work we present a real-time system for imaging of moving targets behind a wall
• The blocks of the system are:
  • Data Acquisition
  • Signal Processing
  • Image Reconstruction
  • Image Processing

• For image reconstruction, we propose a simple and fast algorithm suitable for real-time imaging applications
SAR and MIMO Radar

- In this work MIMO approach is used instead of SAR approach

**SAR (Synthetic Aperture Radar)**
- Provides synthetic aperture by shifting Tx/Rx pair
- Data acquisition takes longer time
- No movement must be present in the scene

**MIMO (Multiple-Input Multiple-Output Radar)**
- More than one Tx/Rx pair are used
- Provides real aperture
- Data acquisition takes shorter time
- Movement may be present in the scene
- Real-time imaging is possible
MIMO Radar - Data Acquisition

• The system consists of 5 transmitters and 5 receivers
• There are separate antennas for Tx and Rx sides
• Type of the antenna is Sinuous and they operate within the 3.1 - 5.6 GHz
• 1st order Gauss pulse is used

In order to detect targets behind the wall:
• All transmitters illuminates the target one by one
• All receivers gather target reflections simultaneously
• At the end of each acquisition cycle a measurement vector $f_{j,k,l}(t)$ is constituted:
  • $j$: cycle index
  • $k$: transmitter index
  • $l$: receiver index
  • $t$: sample index
MIMO Radar - Signal Processing

• Before image reconstruction, some signal processing methods are applied
• First of all, the DC component of each measurement is removed
• The zero-mean signal, \( g_{j,k,l}(t) \) can be expressed as
  \[
  g_{j,k,l}(t) = f_{j,k,l}(t) - \frac{1}{T} \sum_{i=0}^{T-1} f_{j,k,l}(t)
  \]

• In order to detect only moving targets we consider the change (i.e. the difference) between measurements of successive cycles
• The difference signal, \( d_{j,k,l}(t) \), is found as below:
  \[
  d_{j,k,l}(t) = g_{j,k,l}(t) - g_{j-1,k,l}(t)
  \]

• The difference signal, \( d_{j,k,l}(t) \), is then input to an envelope detection algorithm to obtain the envelope signal, \( e_{j,k,l}(t) \).
• There are some differences between SISO back projection and MIMO back projection
• In MIMO radar, a back-projection image is calculated for each Transmitter
• At the end, all Transmitter images are added to find the final image
MIMO Radar – Image Reconstruction: Classical Back Projection

• In the classical TDBP algorithm, every element of the data matrix is propagated back to an appropriate pixel in the image.
• In other words, each pixel value is a sum of certain elements of the data matrix.
• In order to find the value of a pixel $I(x_i, y_i)$
  • Total propagation time for that pixel $\{x_p, y_i\}$ is calculated:
    $$t_i(n) = T_i(n) + R_i(n)$$
  • Total propagation time consists of 2 terms, these are:
    • $T_i(n)$: Propagation time from Transmitter $\{x_T(n), y_T(n)\}$ to the pixel $\{x_p, y_i\}$
      $$T_i(n) = \frac{\sqrt{(x_i - x_T(n))^2 + (y_i - y_T(n))^2}}{c}$$
      $c$: speed of light
    • $R_i(n)$: Propagation time from pixel $\{x_p, y_i\}$ to the Receiver $\{x_R(n), y_R(n)\}$
      $$R_i(n) = \frac{\sqrt{(x_i - x_R(n))^2 + (y_i - y_R(n))^2}}{c}$$
MIMO Radar – Image Reconstruction: Classical Back Projection (cont.)

• When the total propagation time calculated, corresponding sample value is found by dividing it to sampling period:

\[ \frac{t_i(n)}{T_s} \]

\( T_s: \) sampling period

• Finally, pixel values coming from all measurements are added:

\[ I(x_i, y_i) = \sum_{n=1}^{N} B(n, \frac{t_i(n)}{T_s}) \]

\( B: 5x512 \) matrix
\( N: 5 \) (num of total measurements for one BP image)

• These processings are equivalent to drawing ellipses
• An ellipse is drawn for each sample and at the end all ellipses are superimposed
• Total number of ellipse is 5x512=2560 for each sub-BP image
• Transmitter and Receiver are the focuses of the ellipse (\( F_1 \) and \( F_2 \))
• \( r_1+r_2=2a \) is found from round trip time for that sample
MIMO Radar – Image Reconstruction: Fast Back Projection

• TDBP is a computationally expensive method because each pixel value in the image has to be calculated regardless of presence of movement in that region.
• This slows down the image reconstruction algorithm.
• The idea to overcome this problem is to compute the value of only those pixels where there is movement.

• Proposed method:
  • Rather than drawing an ellipse for each sample, draw ellipses for those regions of the signal where there is enough power, i.e. movement

• Steps of the proposed method:
  • Use difference signal, $h(t) = d_{j,k,l}(t)$ (signal before envelope detection)
  • Compute the power of $h(t)$, $P_0$.
  • Divide the signal, $h(t)$, into $D$ segments: $h_1(t),..., h_D(t)$, where the length of each segment is equal to $T/D$,
  • Compute the power of each segment. Thus we obtain $P_d, d=1,...,D$
  • If the ratio $(P_d / P_0)$ is larger than a certain threshold, $T_p$, we decide that there is movement in segment $d$ and vice versa.
  • Finally, draw ellipses for only those segments where movement is detected
MIMO Radar – Image Processing

In order to provide an image which can easily be interpreted by the user, some simple image processing methods are applied at the end.

In theory: Intersection is a “point”:

In reality: Intersection is a “section”

Aim: To find the maximum point in the section: real position of the object

Method: Image processing at the polar domain ("range-azimuth domain")

1) Transition from Cartesian to Polar format

2) Sub-imaging and thresholding

3) Return to Cartesian format

4) Blurring
Experimental Results

- The TWI Radar has been tested in a real environment
- It has been observed that the system can sense through a brick wall of 40 cm thickness.
- The speed performance of the proposed imaging method is compared to TDBP.
- The algorithms are implemented in C++ language and run on an embedded 1GHz ARM Cortex-A8 processor.
- As shown in Table, the proposed image reconstruction method is about 3 times faster than the classical TDBP.

### Speed Evaluation Results (TS =52ps, T=512, M=64 and D=16)

<table>
<thead>
<tr>
<th></th>
<th>TDBP</th>
<th>Proposed Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image reconstruction time per frame [s]</td>
<td>0.23</td>
<td>0.08</td>
</tr>
<tr>
<td>Total time per frame [s]</td>
<td>0.66</td>
<td>0.45</td>
</tr>
</tbody>
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- Very small movements behind the wall such as the movement of the chest of a person due to respiration can be sensed successfully by the system

Imaging result – a person standing 2 m away from the wall
Experimental Results (cont.)

Imaging result – A person is walking with a speed of approximately 0.7 m/s at 2 m distance from the wall in cross-range direction.
Prototype System

System Features:
• Ultra Wideband Radar technology
• Impulse Radio UWB (IR-UWB)
• MIMO Radar structure
• Advanced signal and image processing algorithms

Technical Properties:
• Bandwidth: 2.5 GHz (3.1 GHz – 5.6 GHz)
• Sampling Period: Adjustable between 3.8 GHz - 40 GHz
• Pulse repetition frequency: 48 MHz
• Pulse duration: ~200 picosecond
• Spatial resolution: 4 cm.
• Range: 20 m
• Output power: 5 dBm
• Number of transmitter: 5
• Number of receiver: 5
• Antenna type: Sinuous
• Pulse type: 1st order Gauss
Conclusion and Future Works

• A real-time TWI system using MIMO UWB radar has been developed where we aim to localize moving objects behind a wall.
• The system consists of 4 blocks, namely data acquisition, signal processing, image reconstruction, and image processing.
• For the image reconstruction block a simple and fast algorithm is proposed.
• Experimental results show that moving objects behind a wall can be detected and localized successfully with a decent frame rate.
• Imaging of multiple targets and achieving a higher frame rate are the major goals for the future.
• For imaging of multiple targets, image processing block needs to be improved since, currently, only the most dominant target is shown.
• Processing power of the hardware should be increased for faster imaging.
• Furthermore 3-D imaging seems to be another development direction which also would demand more processing power.
Questions and Answers
Thank you