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Development of Time-Reversal Method for Detecting Multiple Moving Targets Behind the Wall

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Abstract
Through-the-wall Imaging (TWI) is crucial for various applications such as law enforcement, rescue missions and defense. TWI methods aim to provide detailed information of spaces that cannot be seen directly. Current state-of-the-art TWI systems utilise ultra-wideband (UWB) signals to simultaneously achieve wall penetration and high resolution. However, these systems are diffraction-limited and encounter problems due to multipath signals in the presence of multiple scatterers.
This poster introduces a novel time reversal (TR) based algorithm that uses the highly acclaimed MUltiple SIgnal Classification (MUSIC) method to image targets hidden behind an obstruction and achieve superresolution (resolution that beats the diffraction limit). The algorithm utilises spatiotemporal windows to divide the full Multistatic Data Matrix (MDM) into sub-MDMs. The summation of all images obtained from each sub-MDM give a clearer image of a scenario than we can obtain using the full-MDM.

1. Basic Information

(1) Collaborating JHPCN Centers

Kyushu University

(2) Research Areas

☐ Very large-scale numerical computation

(3) Roles of Project Members

- Takeshi Nanri (Kyushu Univ.)
  Parallelization of TR method
- Fumie Costen (Univ. Manchester)
  Tuning of TR method and its application to real cases

2. Purpose and Significance of the Research

There are many imaging systems in the world for see-through the wall or cancer detection such as MRI for medical imaging. However the current technologies are not cheap nor not available everywhere. One of the cheap alternatives to such expensive systems is microwave imaging using the Time Reversal (TR) method which was first introduced in acoustics. TR has found applications in various disciplines ranging from non-destructive testing, underwater communications and medicine. TR has also been studied for Ground Penetrating Radar (GPR) as well as Through the Wall Imaging (TWI). The TR method with some super-resolution techniques such as Decomposition Of the Time-Reversal Operator (DORT in its French acronym) or MUltiple SIgnal Classification (MUSIC) requires more than 150 Fast Fourier Transform and more than 20000 singular value decomposition for a very small imaging system which consists of 13 antenna elements. Therefore the current approach is far from the real-time system due to the long computational time. Furthermore there is a high demand on the detection of multiple moving targets but the work in this field is scarce. The detection of multiple moving targets behind the wall is the one of the most challenging scenarios in through-the-wall microwave imaging. So far Fumie Costen at University of Manchester has developed the spatio-temporal windowing for the differential MDM (multi-static data matrix) for time reversal algorithm to detect multiple moving objects in a simple canonical case. This project will develop and verify an algorithm to detect the multiple moving targets with high computational efficiency.

The successful completion of the project will produce a ground-breaking real-time system for microwave imaging of the multiple moving objects at the theoretical level. The cost for the radar imaging shall be reduced and the radar imaging based on TR shall be available anywhere in the world.

The technology and skills which will be developed for the parallelization of the TR calculation will be applicable to many research area. This parallelization is done in two phases. The first phase distributes independent FFTs and SVDs into multiple processes. Though the parallelization method in this phase is simple, efficient communication is required for broadcasting initial data and gathering results. On the other hand, the second phase decomposes array to enable calculation on much larger cases that require multiple tera-bytes of memory. In this phase, detailed analysis of data dependencies and careful optimization of communication are the keys to achieve sufficient effect of parallelization.

3. Significance as a JHPCN Joint Research Project

Fumie Costen at University of Manchester has the expertise in computation in electromagnetics, especially algorithm development and recently acquiring the techniques to improve the resolution of the radar image behind the wall or in the dispersive media. However the problems which Manchester currently faces cannot be solved at their own side due to the lack of experience in high performance computing and matrix handling. The collaborators in Kyushu University can help her in terms of the parallelization of the code and the SVD handling. As staffs of a supercomputer center, Takeshi Nanri, Kenji Ono and Yoshitaka Watanabe at Kyushu University has been working on the parallelization and optimization of application codes. Therefore, joint research between University of Manchester and Kyushu University will enable the TR method to be fast enough to use it on realistic cases. "International Joint Research Project" of JHPCN will contribute a lot in the progress of this collaborative work.

4. Outline of the Research Achievements up to FY2016

This is a newly started JHPCN project in FY2017. Until FY2016, as a joint work, we had done the following development:

- Developed and examined the performance of the sequential version of TR-method program
- Applied a fundamental process parallelization on the program and examined its effect.

5. Details of FY2017 Research Achievements

5.1 Development and evaluation of sequential TR-method program

5.1.1 Theory

FREE-space imaging is typically employed in conventional radar and synthetic aperture radar (SAR) techniques since distortions in the atmosphere are often negligible. The scene is illuminated with electromagnetic waves which reflect off any target in the medium and return to the receiving antenna giving information about the targets location. Conventional radar, sonar and optical image processes all utilize basic wave physics equations to provide focusing to individual points. Time reversal (TR) methods have become popular for remote sensing because they can take advantage of multipath signals to achieve super resolution (resolution that beats the diffraction limit).

The Decomposition Of the Time-Reversal Operator (DORT in its French acronym) and MUltiple SIgnal Classification (MUSIC) methods are both TR techniques which involve taking the Singular Value Decomposition (SVD) of the Multistatic Data Matrix (MDM) which contains the signals received from the target(s) to be located. The MUSIC imaging method has generated a lot of interests due to its robustness and ability to locate multiple targets. However, these TR-based methods encounter problems when the targets are behind an obstruction, particularly when the properties of the obstruction is unknown as is often the case in TWI applications.

The MUSIC method utilizes the singular vectors of the MDM, whose elements $k_{(s,r)}(t)$, are obtained by transmitting a signal from N TRA antenna elements, one at a time, and recording the response signal in the medium at all antennas, where s is the transmitting antenna and r is the receiving antenna. The full-MDM, $K(t)$, which contains vital information about the targets in the medium, is represented by $K(\omega)$ in the frequency domain.

In TWI applications, the reflections from the wall dominate the MDM, $K(t)$, in power which is crucial for the application of the MUSIC methods. Hence, rather than the global information contained in the full-MDM, we obtain localized information from various parts of the scattering medium in the sub-MDMs, which reduces the number of targets to be detected at one time.

5.1.2 Algorithm

We select the Hanning window [6] as our time-window. By subsequent time-shifting, we obtain temporal-windows to completely cover the whole signal duration of interest. The mth time-window is obtained as

$$W_m(t) = 0.5\left(1 - \cos\left(\frac{2\pi(t-\tau_m)}{P}\right)\right) \tag{1}$$

for $(P(m-1))/2 \le t \le P + (P(m-1))/2$ and otherwise $W_m(t)=0$, where τ_m is the time shift and P is the window interval. In order to avoid loss of data, the time-windows are shifted in time from one another to ensure that the addition of the time-windows gives a magnitude of 1. Hence, the time shift is defined as $\tau_m = P(m-1)/2 \, (1 \le m \le M)$ where $M = \lfloor T/0.5P - 1 \rfloor$is the number of time-windows needed to cover the time simulated, T, for the scenario, and $\lfloor\ \rfloor$ represents a floor function that maps a real number to the largest previous integer.

By multiplying the Hanning windows $W_m(t)$ by the elements of the full-MDM $k_{(s,r)}(t)$, one at a time, we obtain M sub-MDMs as $K_m(t,P)$. We further segment $K_m(t,P)$ in space by selecting elements of $K_m(t,P)$ obtained from a set of N_s antennas where $1 \le N_s \le N$. Hence, for $K_m(t,P)$, we obtain the lth sub-MDM as

$$\boldsymbol{K}_{m,l}(t,P,N_s) = \begin{pmatrix} k_{l,l}(t)W_m(t) & \cdot\ \cdot & k_{l,L}(t)W_m(t) \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ k_{L,l}(t)W_m(t) & \cdot\ \cdot & k_{L,L}(t)W_m(t) \end{pmatrix} \tag{2}$$

where $L = N_s - 1 + l$ and $1 \le l \le N + 1 - N_s$.

Assuming the excitation pulse width is Υ, the minimum size of the time-window is chosen to be Υ. Hence

$$P \geq \Upsilon.$$

This ensures that a single time-window covers the initial excitation signal transmitted from the TRA antennas.

Furthermore, since the MUSIC methods utilise the singular vectors in the null subspace, the minimum value of N_s should be greater than the number of singular values in the signal subspace N_t of the full-MDM to ensure that we retain noise in the sub-MDMs. Therefore

$$N_s > N_t. \tag{4}$$

By performing the FFT on the elements of sub-MDM $K\_(m,l)\ (t,P,N\_s\ )$ we obtain $K\_(m,l)\ (\omega,P,N\_s\ )$. Furthermore the SVD on $K\_(m,l)\ (\omega,P,N\_s\ )$ gives

$$\boldsymbol{K}_{m,l}(\omega, P, N_s) = \boldsymbol{U}(\omega, m, l)\boldsymbol{A}(\omega, m, l)\boldsymbol{V}^{\dagger}(\omega, m, l) \tag{5}$$

where $\mathrm{A}(\omega,m,l)$are $N\_s\times N\_s$ real diagonal matrices containing the singular values in descending order and, $\mathrm{U}(\omega,m,l)$and $\mathrm{V}(\omega,m,l\ )$are $N\_s\times N\_s$ unitary matrices containing the left and right singular vectors of $u\_n\ (\omega,m,l)$ and $v\_n\ (\omega,m,l)$ for $1\leq n\leq N\_s$, respectively. We define the total sub-CF-MUSIC imaging functional as the summation of all sub-CF-MUSIC imaging functionals to obtain

$$\boldsymbol{M}_{\Gamma}(\overline{r}, \omega_c, P, N_s) = \sum_{l=1}^{L}\sum_{m=1}^{M}\left[\sum_{n=N_t(\omega_c)+1}^{N_s} \boldsymbol{g}^{\dagger}(\overline{r}, \omega_c)\cdot \boldsymbol{u}_n(\omega_c, m, l)\right]^{-1} \tag{6}$$

where ω_c is the centre frequency of interest. Similarly, the summation of the sub-UWB-MUSIC imaging functionals gives the total sub-UWB-MUSIC imaging functional as

$$\boldsymbol{M}_{\Gamma_{UWB}}(\overline{r}, P, N_s) = \sum_{l=1}^{L}\sum_{m=1}^{M}\left[\int_{\Omega}\sum_{n=N_t(\omega)+1}^{N_s} \boldsymbol{g}^{\dagger}(\overline{r}, \omega)\cdot \boldsymbol{u}_n(\omega, m, l)d\omega\right]^{-1} \tag{7}$$

where Ω is the frequency range of interest.

5.1.3 Results

Figure 1 shows the geometry of a scenario with one well-resolved PEC sphere, whose radius is 15mm and conductivity is 107 S/m, in a homogeneous medium (free-space) hidden behind a brick wall.

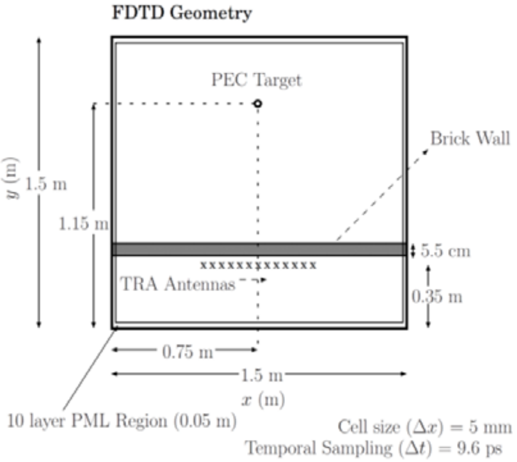
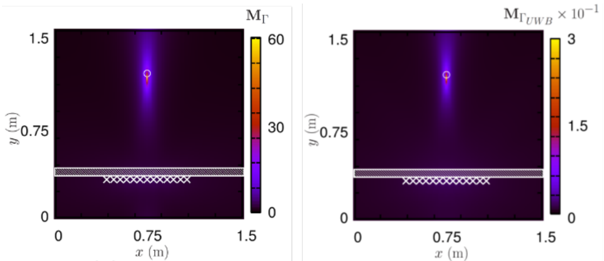


Figure 1 The geometry of the FDTD scenario with one PEC sphere behind a brick wall

Figure 2 shows the total sub-CF-MUSIC and total sub-UWB-MUSIC (from 0.3 to 4.8 GHz) images when $N_s = 7$ and $P = 8\gamma$. The total sub-CF-MUSIC and total sub-UWBMUSIC imaging functional yield images that accurately locate the target.



(a) CF-MUSIC (b) UWB-MUSIC

Figure 2 The total sub-CF-MUSIC and total sub-UWBMUSIC images produced when P=8γ and N_s=7, where × represents the TRA antennas' locations and ∘ represents the target location

5.2 Parallelization of TR-method program

After the Progress Report, we have been working on further parallelization, and detection of multiple moving targets. In that process, we found some severe failures in the original code. Since the structures of some kernel loops have been changed, we needed to parallelize the code with new approaches. Therefore, we did not have sufficient time for applying the code on multiple moving targets.

5.2.1 Scalability analysis of the modified code

To find the target loop of parallelization, we have the program into 14 sections, and the performance of each section of the OpenMP version is examined. We used one node of ITO System, the new supercomputer in Kyushu University. Table 1 shows the execution time of top three time-consuming loops, and the total execution time of the program with an input file for 396x411 space with 31 antennas and the temporal window interval is 320.

Table 1 Execution time of sections with 36 threads

Section	**Time (sec.)**
3	490
7	676
14	897
Total	2137

As shown in the table, these three sections dominate most of the total execution time. Therefore, we have applied parallelization mainly on loops in these sections.

In addition to that, we have studied on the memory consumption of the code to determine the arrays to be distributed among processes. As a result of the study, two arrays, Steert and Steerw were found to be the ones that dominated the memory usage of the code. Sizes of these arrays can be calculated as follows:

- Steert: nx * ny * maxfreqs * nant * ndata
- Steerw: nx * ny * maxfreqs * nant

Where nx and ny are the lengths of X and Y dimensions of the field, maxfreqs is the maximum number of frequencies to be examined, nant is the number of antennas and ndata is the number of datafiles to be calculated. The data types of Steert is REAL and that of Steerw is COMPLEX.

With the input file for 396x411 space with 31 antennas, 1600 frequencies at maximum and 3 data files to be examined, the memory consumptions of the arrays were:

- Steert: about 96GB
- Steerw: about 64GB

If the code is parallelized without distributing these arrays, each process needs to allocate these arrays. On subsystem A of ITO, each node consists 192GB of memory. That means only one process can be run on each node.

On the other hand, if these arrays are distributed, memory consumption per process can be reduced. It allows the users to adjust the ratio of the number of processes and the number of threads to achieve higher efficiency. However, this requires additional communication among processes to exchange intermediate results to complete calculation.

5.2.2 Parallelization method

At this point, we have done the following data distribution and loop paralllelizations:

1) Distribute Steert among processes

   Loops that stores or refers values of Steert can be easily parallelized among processes so that each process refers to the values that have been stored by the process itself. On the other hand, distribution of Steerw required significant amount of communication among processes. Instead, allocation of Steerw is delayed until the end of Section 7 where Steert is deallocated. In addition to that, since Steerw is constructed by applying FFT on Steert, a temporal array SubSteerw is allocated to store the results of FFTs on each node. Then, after deallocation of Steert and allocation of Steerw, MPI communications are inserted to copy values in SubSteerw to Steerw so that every process have copies of those data. With these techniques, the peak memory consumption per process has become almost equal to the size of Steerw and SubSteerw.

2) Parallelize loops for simulating each antenna in Section 3 and Section 7
   Section 3 initializes the source field, while Section 7 applies FFT to the simulated field. These sections consist a loop for calculation on each antenna. Therefore, these loops are parallelized in blocks among processes. Speed-up of computation time with these parallelization is, theoretically linear to the number of processes, until it reaches to the number of antennas. However, these parallelizations require additional communications that reduces the speedup ratio.

3) Hierarchically apply parallelization on a loop nest in Section 14
   Section 14 is the main part of the program. It applies SVD (singular value decomposition) and FFT on the field to determine the location of the target. This section is constructed by a nest of loops in which, a loop calculates on each window and within the loop, SVD is applied on each frequency to be examined. Therefore, in our parallelization, processes are divided into Nwin (number of windows) groups, and each group calculates SVDs on Nfreqs (number of frequencies to be examined) in parallel. After calculation of SVDs, each group applies an FFT on the results. Theoretically, the speedup ratio of the SVD calculation is estimated to be Nwin * Nfreqs, while that of FFT calculation is Nwin. Also, additional communication of MPI_Allgatherv is required to gather results on each window.

5.2.3 Results of parallelization

Table 2 shows the execution time of the parallelized code with the same input data mentioned in 5.1.2. In the table, “1proc” means the time with 1 node with 1 process and 36 threads. Other columns show the times with 9, 18 and 36 nodes with 2 processes per node. So, the number of threads are 18 for these results.

Table 2 Effect of parallelization on TR-method

Section	1proc (sec)	18procs (sec)	36procs (sec)	72procs (sec)
3	490	36	21	24
7	676	132	113	113
14	897	85	49	32
Other	74	10	9	9
Total	2137	263	192	178

From these results, we could see sufficient speedup with 9nodes. However, we also see saturation of the speedup on larger number of nodes. Possible reasons are as follows:

- In Section 3 and Section 7, The speedup is limited to the number of antennas (= 31) .
- In section 14, the speedup of FFT calculation is limited to the number of windows (= 9).
- Communications for tens of GB of data are required.

6. Progress of FY2017 and Future Prospects

In FY2017, we could achieve more than 10 times of speedup with MPI parallelization. We are now modifying the code so that it can detect the multiple moving targets. The structure of the code will be almost the same. However, it will require much more amount of computation. Therefore, the techniques we have established in this project will help us to speedup it.

7. List of Publications and Presentations

(1) Journal Papers

(2) Conference Papers

(3) Oral Presentations

(4) Others