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14. ABSTRACT
In this project, we investigated time reversal (TR) based signal processing theory and algorithm development for target detection, localization, imaging, and interference cancellation in the electromagnetic domain. We conducted a thorough study of time reversal for these applications, developed new suites of detection and imaging algorithms and derived analytical expressions quantifying their performance, confirmed the analytical results with extensive numerical simulations, and demonstrated the gains in performance over conventional methods using real world

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Electromagnetic Time Reversal for Detection, Localization, and Imaging Final Report

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List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

[1] Y. Jin, J. M. F. Moura, and N. O'Donoughue, "Time reversal in multiple input multiple output radar," IEEE Journal of Selected Topics in Signal Processing, vol. 4, no. 1, pp. 210-225, Feb 2010

[2] Y. Jin and J. M. F. Moura, "Time reversal detection using antenna arrays", IEEE Transactions on Signal Processing, vol. 57, no. 4, pp. 1396-1414, April 2009.

[3] J. M. F. Moura and Y. Jin, "Time reversal imaging by adaptive interference canceling", IEEE Transactions on Signal Processing, vol. 56, no. 1, pp. 233-247, January 2008

[4] J. M. F. Moura and Y. Jin, "Detection by time reversal: single antenna", IEEE Transactions on Signal Processing, vol. 55, no. 1, pp. 187-201, January 2007

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[1] Y. Jin, J.M.F. Moura, Y. Jiang, J. Zhu, and D. Stancil, "Time reversal target focusing in spotlight SAR", 15th Adaptive Sensor Array Processing Workshop, MIT Lincoln Lab, Lexington, MA, June 5-6, 2007

[2] J. M. F. Moura, Y. Jin, D. Stancil, J. Zhu, A. Cepni, Y. Jiang, "Time reversal adaptive interference cancellation and detection", 13th Annual Workshop on Adaptive Sensor Array Processing (ASAP), MIT Lincoln Laboratory, Lexington, MA, June 7-8, 2005

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[1] Y. Jin, J. M. F. Moura, N. O'Donoughue, J. Harley, "Single antenna time reversal detection of moving target," International Conference on Acoustics, Signal, and Speech Processing, pp. 3558-3561, Dallas, TX March 15 - 19, 2010

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(d) Manuscripts

[1] Y. Jin and J. M. F. Moura, A. Cepni, Y. Jiang and D. Stancil, "Time reversal detection in clutter: theory and experiments", IEEE Transactions on Aerospace and Electronic Systems, vol. 46, no. 4, December 2010 (to appear).

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Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Yi Jiang	1.00
Ben Henty	0.50
Matthew J. Chabalko	0.50
Nicholas O'Donoughue	0.00
Amhet Cepni	1.00
FTE Equivalent:	**3.00**
Total Number:	**5**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Yuanwei Jin	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Jose M. F. Moura	0.20	No
Jimmy Zhu	0.15	No
Dan Stancil	0.15	No
FTE Equivalent:	**0.50**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Amandianeze Nwana	0.25
Michael Wahl	0.25
Daniel Lim	0.25
FTE Equivalent:	**0.75**
Total Number:	**3**

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Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Matthew J. Chabalko
Nicholas O'Donoughue
Total Number: 2

Names of personnel receiving PHDs

NAME
Yi Jiang
Ben Henty
Ahmet Cepni
Total Number: 3

Names of other research staff

NAME	PERCENT_SUPPORTED	
Yuanwei Jin	1.00	No
FTE Equivalent:	**1.00**	
Total Number:	**1**	

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Electromagnetic Time Reversal Imaging: Analysis and Experimentation

Final Report

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Contents

1. Abstract

In this project, we investigated time reversal (TR) based signal processing theory and algorithm development for target detection, localization, imaging, and interference cancellation in the electromagnetic domain. We conducted a thorough study of time reversal for these applications, developed new suites of detection and imaging algorithms and derived analytical expressions quantifying their performance, confirmed the analytical results with extensive numerical simulations, and demonstrated the gains in performance over conventional methods using real world electromagnetic data. The algorithms developed included TR-channel matched detectors, TR adaptive interference canceller (TRAIC) and TR beamforming for imaging and localization, and TR-SAR for improved ghost removal in SAR imaging. Our algorithms, analytical, and experimental findings have been consistently summarized in the annual reports we have submitted and in over 30 publications submitted to the technical literature (Journals and Conferences.) This Final Report summarizes the major achievements of the program.

2. Statement of the Problem Studied

The primary goal of this program was to investigate time reversal based target detection, localization, imaging, and interference cancellation schemes in complex scattering environments in the electromagnetic domain. Our investigation focused on signal processing algorithm development, electromagnetic wave propagation analysis and simulation, and experimental verification.

Time reversal is a time domain signal transmission scheme that can be described as follows: a signal source is transmitted in a multipath rich scattering environment and is received by a receiver. The received signal is time reversed, i.e., first in last out, energy normalized, and retransmitted into the same propagation medium. This re-transmitted signal will re-trace the original propagation paths and focuses at the location of the original transmitter. Figure 1 shows the iterative procedure of signal probing, time reversal retransmission, and signal focusing.

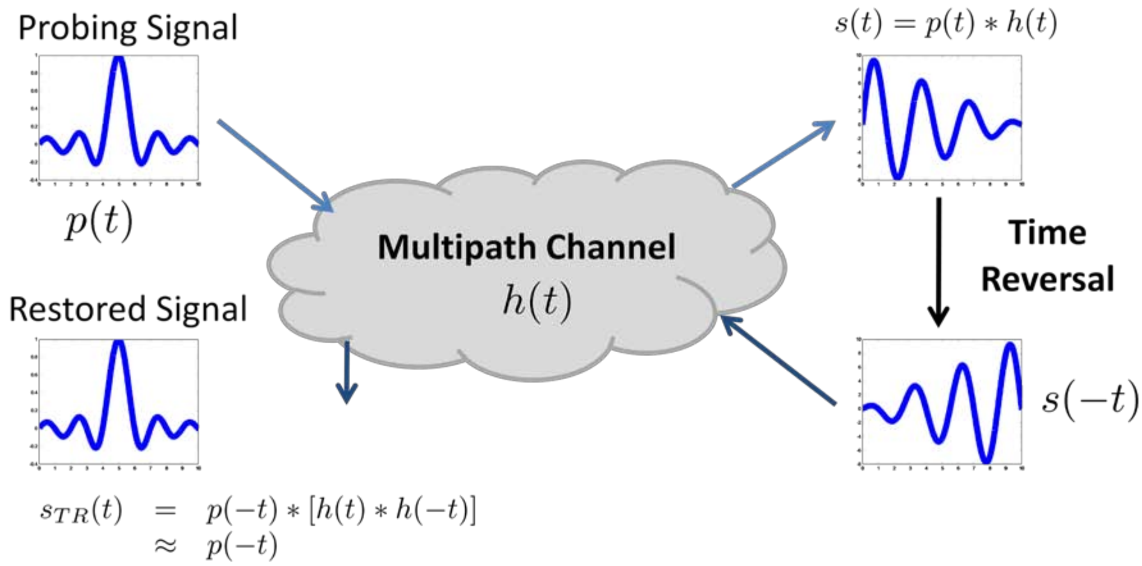

Figure 1. Illustration of time reversal focusing

This seemingly simple operation and processing can achieve temporal and spatial energy focusing. This focusing phenomenon has been verified in various wave propagation experiments for various wave modalities including electromagnetic waves, acoustical waves, and elastic waves. Super-resolution, i.e., the spatial and temporal focusing gives rise to higher resolution, beyond the limit of classic Rayleigh resolution.

This project went through a Phase I and a Phase II. We demonstrated in Phase I quantitatively that **time reversal detection provides significant gains over conventional matched filter detection**. Our work developed time reversal (TR) based algorithms to *detect pointwise* targets in highly cluttered environments. In Phase I, we focused on *single* transmit single receive sensors in the *electromagnetic* (EM) domain with *wideband* signals. We developed two time reversal detectors: the ideal time reversal channel matched detector that assumed perfect knowledge of the scattering environment and the time reversal generalized likelihood ratio test that assumes no knowledge of the scattering environment and estimates the channel by maximum likelihood techniques. We compared these detectors to the matched filter, the channel matched change detector, and the energy detector. Our analysis quantified the detection gains of the time reversal detectors over the conventional detectors. The analysis was confirmed by comprehensive simulations depicting realistic EM environments and by extensive EM experimental studies carried out indoors in the Carnegie Mellon Time Reversal Laboratory. Besides showing that time reversal provides a significant gain in detection performance, our work verified that higher levels of clutter increase these gains, and that TR-based detectors are more robust to the relative target – clutter – sensor geometry.

Our Phase II work extended our Phase I work in a number of dimensions. In Phase II, we demonstrated the gain provided by time reversal over conventional algorithms in detection/ localization/ and imaging of targets in highly cluttered environments. We demonstrated the detection/ localization/ imaging performance gains provided by time reversal over conventional techniques by carrying out: (i) Theoretical analysis of the time reversal based algorithms; (ii) Simulations that tested the time reversal and conventional algorithms in a number of realistic scenarios; and (iii) Experimentation in indoors and outdoors environments of the time reversal and conventional algorithms with a variety of targets and scatterers.

We developed new suites of time reversal based algorithms that can detect/ localize/ and image pointwise as well as extended targets in realistic cluttered environments, in particular, TRAIC, the time reversal adaptive interference canceller, and TR-SAR, a time reversal based SAR algorithm. TRAIC images objects in highly reverberant environments by focusing energy on the object rather than the scatterers. TR-SAR extends SAR by removing ghosts and other distortions due to scatterers.

We contrasted TR imaging with SAR imaging. TR-SAR is a SAR imaging like system combined with time reversal. In TR_SAR, like in SAR, a moving array generates a synthetic aperture and transmits a pulse sequence with a given pulse repetition frequency. Unlike SAR, however, TR-SAR has two pulse transmissions: first, it transmits a chirp like signal, records the returned echoes, and then delays, time reverses, and retransmits them. There are a number of theoretical and practical issues associated with TR-SAR that our work addressed. Conventional SAR is narrowband and the pulses are gated to record the echoes scattered from a given range. TR-SAR transmits broadband signals and records the scattered returns over a longer period of time to capture the significant scattered returns (multipath) from a given range, since scattering (multipath) spreads the signal. We studied the tradeoffs and impact of different TR-SAR systems parameters, e.g., range of admissible values for the PRF and bandwidth versus range and cross range resolutions. We designed two versions of the TR-SAR system: (i) the direct TR-SAR is the system described in the previous paragraph – the retransmitted signals are the time reversed versions of the received echoes; and (ii) the waveform reshaped TR-SAR where the retransmitted signals are reshaped versions of the time reversed echoes. The reshaped waveforms are designed to reduce the direct returns from unwanted clutters (but not the secondary scattering from these to the targets of interest). These waveform reshaped algorithms build on the TRAIC (time reversal adaptive interference canceller) algorithm. We contrasted the performance of conventional SAR with the performance of the TR-SAR imaging system as the scattering environment got more complex. For progressively more complex scenarios, the performance of conventional SAR dropped significantly, while, on the contrary, the performance of TR-SAR imaging improved, confirming for imaging the conclusions achieved in Phase I for detection.

Our work considered targets ranging from simple geometry, with smooth corners and edges, like cylinders with circle or oval cross-sections, to targets with more complex geometries with sharp edges and/ or corners, more complex cross-sections, and made of different materials.

The scattering environments varied from indoor Laboratory space populated by rods of different materials, a mix of potted trees and pipes, potted trees under air flow from a fan to simulate wind, highly reverberant environments like ducts, to outdoor environments (Raytheon Missile Division outdoors range) with open field, trees, and targets including trucks.

3. Summary of the Most Important Results

A list of the most important results is shown below, with relevant details following.

1. Stationary target detection: Single antenna detection and antenna array detection
2. Beamforming imaging by adaptive interference cancellation
3. Synthetic aperture radar imaging and ghost image removal
4. Multiple input multiple output (MIMO) time reversal detection
5. Moving target detection by time reversal
6. Other applications

3.1. Stationary target detection by time reversal

We studied the binary hypothesis test of detecting the presence or absence of a target in a highly cluttered environment by using time reversal. We started with the single antenna detection problem, we then extended it to antenna array detection.

In single antenna detection, we considered two versions of the test—target channel frequency response assumed known or unknown—and, for each version, contrasted two approaches: conventional detection (where no time reversal occurs) and time reversal detection. This led to 4 alternative formulations for which we derived the optimal detector and the generalized likelihood ratio test, when the target channel frequency response is known or unknown, respectively. We derived analytical expressions for the error probabilities and the threshold for all detectors, to the exception of the time reversal generalized likelihood ratio test. Experiments with real world electromagnetic data for two channels (free space with a target immersed in 20 scatterers; and a duct channel) confirmed the analytical results and showed that time reversal detection provided significant gains over conventional detection. This gain was explained by the empirical distribution or *type* of the target channel frequency response—richer scattering channels induce *types* with heavier tails and larger time reversal detection gains.

Next, we considered the detection problem using a multi-static configuration with receive and transmit *arrays* of antennas. We derived two array detectors: the time-reversal channel matched filter when the target channel response is known; and the time-reversal generalized-likelihood ratio test (TR-GLRT) when the target channel response is unknown. The noise added in the initial probing step to the time-reversal signal makes the analysis of the TR-GLRT detector non trivial. We derived closed form expressions for the signal-to-noise ratio gain provided by this detector over the corresponding conventional clutter subtraction energy detector in the two extreme conditions of weak and strong (electronic additive) noise and showed that time reversal provided, under weak noise, the optimal waveform shape to probe the environment. We analyzed the impact of the array configuration on the detection performance. Finally, experiments with electromagnetic data collected in a multipath scattering laboratory environment confirmed our analytical results. Under the realistic conditions tested, time reversal provided detection gains over conventional detection that ranged from 2 to 4.7 dB.

3.2.Beamforming imaging by interference cancellation

We developed the *Time Reversal Adaptive Interference Canceller* (TRAIC) time reversal beamformer (TRBF), a new algorithm to detect and locate targets in rich scattering environments. TRBF utilizes time reversal in two stages: (1) *Anti*-focusing: TRAIC time reverses and then reshapes the clutter backscatter to *mitigate* the clutter response; (2) *Focusing*: TRBF time reverses the residual backscatter to *focus* the radar image on the target. Laboratory experiments with electromagnetic radar data in a highly cluttered environment confirmed the superiority of TRAIC-TRBF over conventional direct subtraction beamform imaging.

3.3. Synthetic aperture radar (SAR) imaging for point targets and extended targets

We focused on point target imaging and extended target imaging in the context of synthetic aperture radar (SAR). For point targets, we developed *time reversal* spotlight synthetic aperture radar (TR-SAR) for target focusing and ghost images removal in SAR. Conventional SAR is not designed for imaging targets in a rich scattering environment. In this case, ghost images due to secondary reflections appear in the SAR images. We showed how, from a rough estimate of the target location obtained from a conventional SAR image and using time reversal, TR-SAR focuses on the target with improved resolution and reduces or removes ghost images. Verification with experimentally measured electromagnetic data demonstrated the success of TR-SAR.

Next, we developed a time reversal SAR (TR-SAR) imaging algorithm for extended (nonpoint-like) targets in rich multipath scattering. We tested the TR-SAR algorithm using experimental electromagnetic data collected in a laboratory environment where the extended target (a galvanized steel sheet) is surrounded by a large amount of PVC rods. Our experiments showed that the collected EM data in frequency and aperture after TR-SAR processing produces a higher resolution, cleaner target map compared with conventional SAR images.

3.4.MIMO radar detection by time reversal

Multiple-input multiple-output (MIMO) radar is an emerging active sensing technology that uses diverse waveforms transmitted from widely spaced antennas to achieve increased target sensitivity when compared to standard phased arrays. We combined MIMO radar with time reversal to automatically match waveforms to a scattering channel and further improve the performance of radar detection. We established a radar target model in multipath rich environments and developed likelihood ratio tests for the proposed time-reversal MIMO radar (TR-MIMO). Numerical simulations demonstrated improved target detectability compared with the commonly used statistical MIMO strategy.

3.5.Hidden target classification

We developed an M-ary hypothesis testing algorithm for classifying radar backscatter signals from hidden targets in a rich scattering environment using time reversal. The target recognition algorithm classified from which among *M* classes the radar backscatter from an unknown object arose. The proposed time reversal target classifier is, in essence, a correlator that calculates the cross-correlation of the normalized target signature waveforms with a data dependent quantity obtained from the backscatter measurements. The algorithm requires *a priori* empirical statistical knowledge of the scattering channel, which is dependent on the configuration of the scatterers in the environment. By incorporating time reversal, the proposed algorithm provides a significant performance improvement compared with conventional methods. Proof of concept was provided using electromagnetic data collected in a laboratory environment.

3.6. Moving target detection

In addition to stationary target detection, we considered a moving target detection using time reversal in a dense multipath environment. We showed that the Doppler shift in the time reversal re-transmission simplifies the detector design, yet still achieves the focusing effect. Thus, the Doppler diversity can be utilized to achieve higher target detectability by time reversal

3.7. Other applications: wireless communication, biomedical imaging, structure health monitoring

Beyond the applicability of time reversal detection, imaging, and classification, we investigated research problems in wireless communications, breast cancer detection, and infrastructure health monitoring as a continuation of the work under this Time Reversal Initiative. Our work in these directions is a direct spinoff from the DARPA/ARO supported activities and represents a transfer of the technology from the DARPA/ARO grant to other areas with potential commercial applications.

3.7.1. UWB wireless communication

We studied the multiple antenna time reversal downlink transmission in an ultra-wideband (UWB) communication system that consists of access points and users. The access point has multiple antennas and the user has a single antenna. We designed the UWB beamformer that focuses on the intended user while minimizing its interference on unintended users and eavesdropping access points. We showed that the designed UWB beamformer is equivalent to the time reversal focusing and nulling schemes and yields better performance than the conventional delay line wideband beamformer. We verified our results using experimentally measured electromagnetic data in an indoor environment.

3.7.2. Breast cancer detection

Microwave radiation is well known as a diagnostic imaging method for many medical applications, for example, early stage breast cancer detection. Microwave detection of breast tumors is a non-ionising, potentially low cost, *in vivo* modality that relies on the dielectric contrast between healthy and malignant breast tissues. The scattering environment in a breast often appears to be inhomogeneous due to changing dielectric properties of the breast tissues. Time reversal (TR) is an adaptive waveform transmission scheme that utilizes the rich scattering medium to best match to the target response. We developed the microwave time reversal beamformer for breast tumor detection. The TR beamforming scheme is examined based upon a breast model using the twodimensional finite-difference time-domain (FDTD) method. We showed that time reversal microwave beamforming is a more robust, higher resolution imaging scheme than conventional beamforming schemes.

3.7.3. Focusing elastic waves in pipelined infrastructures

The volatile nature of natural gas makes it extremely important to ensure that distribution pipelines remain free from defects, as leakage can result in explosions. Many current methods for testing buried pipelines rely on periodic excavation of a section of pipe and attachment of large acoustic or magneto-restrictive sensors. These systems, while reliable, suffer from a high cost-per-test ratio. Our group hopes to reduce the power constraints of such a detection system, in order to allow for permanent installations that monitor the pipelines continuously. We proposed to use Time Reversal, a signal processing technique, in order to achieve this improvement. Our research focuses on the modes generated by various acoustic probing signals, and the echoes received with and without Time Reversal. We argue that TR will be most beneficial when there are several dispersive modes present, a scenario avoided in conventional techniques. We presented simulation results for the analysis of wave modes in a cylindrical pipe before and after Time Reversal using PZFlex.

3.7.4. Cognitive sensor network for structure defect classification

We developed a framework of a cognitive sensor networks system for structure defect monitoring and classification using guided wave signals. Guided ultrasonic waves that can propagate long distances along pipelined structures have been widely studied for inspection and detection of structure damage. Smart ultrasonic sensors arranged as a spatially distributed cognitive sensor network system can transmit and receive ultrasonic guided waves to interrogate structure defects such as cracks and corrosion. A distinguishing characteristic of the cognitive sensor network system is that it adaptively probes and learns about the environment, which enables constant optimization in response to its changing understanding of the defect response. We developed a sequential multiple hypothesis testing scheme combined with adaptive waveform transmission for defect monitoring and classification. The performance is verified using numerical simulations of guided elastic wave propagation on a pipe model and by Monte Carlo simulations for computing the probability of correct classification.

4. Open Problems and Future Research

There are still many open problems in this exciting research area using time reversal. One of the problems we believe needs particular attention is imaging the shadow area of an extend target. Extended target image reconstruction is not a trivial extension of the point target imaging problem. The general question is “can we see the back of the target from limited view angles?” We believe that time reversal can improve imaging the shadow region for extended targets in complex scattering environments. A viable solution to this problem will substantially improve the imaging capabilities of radar sensors and has significant impact in military and commercial applications. Our preliminary work in this direction shows promising results.

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1. **Y. Jin,** J. M. F. Moura, and N. O' Donoughue, "Time reversal in multiple-input multiple-output radar", IEEE Journal of Selected Topics on Signal Processing, vol. 4, no. 1, pp. 210-225, Feburary 2010
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