REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	3. DATES COVERED END DATE
20221101	Final	20170501	20220831

4. TITLE AND SUBTITLE
Four Dimensional Maritime Sensing and Imaging Systems with Photon Information Optimization

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
N00014-17-1-2405	N00014-17-1-2405	
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Bahram Javidi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Connecticut Office Sponsored Programs 438 Whitney Rd Extension Unit 1133 Storrs, CT 06269-1133	5629560

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Office of Naval Research 875 N. Randolph Street, Suite 1425 Arlington, VA 22203-1995	ONR	

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; Distribution is Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The major goals and objectives of the project are to investigate a novel four-dimensional (4D) sensing approach based on 3D photon counting time varying integral sensing and imaging architecture with distributed sensors. This novel approach can function with a small number of photons and poor SNR and results in a substantial increase in the ability for detection of underwater signals, objects, and sources.

15. SUBJECT TERMS
Four-dimensional (4D) sensing, 3D integral sensing and imaging, time varying integral sensing and imaging, detection of underwater signals, objects, and sources.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	UU (Unclassified Unlimited)	

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*

Page 1 of 2

PREVIOUS EDITION IS OBSOLETE.

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

Final Report on ONR Project N00014-17-1-2405
Title: Four Dimensional Maritime Sensing and Imaging Systems with Photon Information Optimization

Submitted by:

Dr. Bahram Javidi
Board of Trustees Distinguished Professor
Electrical and Computer Engineering Department
University of Connecticut, U-4157
Storrs, Connecticut 06269-4157
Bahram.Javidi@UCONN.edu
www.mosis.engr.uconn.edu

Report Summary:

The major goals and objectives of the project are to investigate a novel four-dimensional (4D) sensing approach based on 3D photon counting time varying integral sensing and imaging architecture with distributed sensors. This novel approach can function with a small number of photons and poor SNR and results in a substantial increase in the ability for detection of underwater signals, objects, and sources. In addition, for a known transmitted signal and/or spatial 3D structure within the field of view of the sensor system, the captured signals and/or images can provide insight about the nature of turbulence. We wish to demonstrate that there are substantial benefits in using four-dimensional sensing for visualization, seeing through obscuration, turbidity, and real-time underwater object identification and tracking. Our sensing method combines time domain data for the case of time varying underwater signals with multi-view 3D integral sensing to record parallax and to extract range and 3D profile information of sources, targets, and scenes. Unlike LADAR, which uses active illumination to measure time of flight, our proposed sensing approach uses randomly distributed sensors to measure both the direction (angular information) and intensity information of arriving photons plus time domain fluctuations. The proposed 4D receiver can determine the range, angular direction, and overall 3D coordinates of a modulated transmitting point source for signal detection, and/or the 3D scene profile of underwater objects.

Accomplishments

What were the major goals and objectives of the project?

Research for advanced underwater signal detection systems is becoming increasingly important due to the growing popularity and widespread use of autonomous or unmanned underwater vehicles for marine exploration and other applications. In underwater communication, acoustic signals are commonly used for transmission due to their long propagation length; however, acoustic signals are greatly limited by bandwidth limitations, low data rate, and large transmission delay, which degrade the quality of the signal. On the other hand, underwater wireless optical communication (UWOC) using photodiodes or photomultipliers enables high data rate, low latency, and highly secure communication compared with conventional acoustic communication methods. Despite these advantages, UWOC systems also have their own difficulties as light cannot propagate as far as acoustic waves due to various physical processes, including absorption, scattering, and beam divergence in the underwater medium. Moreover, an optical signal propagating in an aquatic medium suffers from attenuation and broadening in the spatial, temporal, angular, and polarization domains. The wavelength-dependent attenuation and broadening are due to absorption and multiple scattering of light by organic and inorganic particulates in the turbid media. As a result, underwater signal detection in degraded environments proves to be a difficult task.

The major goals and objectives of the project are to investigate a novel four-dimensional (4D) sensing approach based on 3D photon counting time varying integral sensing and imaging architecture with distributed sensors. This novel approach can function with a small number of photons and poor SNR and results in a substantial increase in the ability for detection of underwater signals, objects, and sources. In addition, for a known transmitted signal and/or spatial 3D structure within the field of view of the sensor system, the captured signals and/or images can provide insight about the nature of turbulence. We wish to demonstrate that there are substantial benefits in using four-dimensional sensing for visualization, seeing through obscuration, turbidity, and real-time underwater object identification and tracking. Our sensing method combines time domain data for the case of time varying underwater signals with multi-view 3D integral sensing to record parallax and to extract range and 3D profile information of sources, targets, and scenes. Unlike LADAR, which uses active illumination to measure time of flight, our proposed sensing approach uses randomly distributed sensors to measure both the direction (angular information) and intensity information of arriving photons plus time domain fluctuations. The proposed 4D receiver can determine the range, angular direction, and overall 3D coordinates of a modulated transmitting point source for signal detection, and/or the 3D scene profile of underwater objects.

What was accomplished towards achieving these goals?

Optical signal detection and sensing in a scattering medium such as turbid water, fog, and biological tissue have great importance in biological imaging, remote sensing, and underwater communication applications. Optical sensing and imaging methods are strongly challenged by the scattering medium, which degrades the performance of the underwater communication systems. To overcome these challenges, researchers have used a range of optical sensing and computational imaging techniques. Optical techniques based on time-resolved imaging, coherent gated imaging for depth-resolved imaging through scattering medium, and optical coherence methods have significantly improved signal detection.

In optical imaging-based methods, researchers have demonstrated various techniques to address the problem of underwater signal detection in turbid water. These strategies focus on the mitigation of the effects of turbidity using methods such as peplography or polarization descattering techniques. Moreover, 3D imaging strategies can capture 3D information of the scene including the intensity and angular information of the beam, which is not possible using approaches that only capture intensity information of the beam. Thus, a 3D approach may achieve better performance for underwater signal detection in turbid conditions.

Polarization difference imaging is an optical imaging technique that mainly eliminates the scattered photons and enhances the visibility of polarized ballistic photons. In recent years, several studies have been proposed to exploit the difference in polarimetric responses between the backscatter and the target for active polarimetric imaging systems. Likewise, integral imaging has been applied to several applications which illustrate better performance in degraded environments such as turbid medium, low light conditions, and in the presence of occlusion. Through integral imaging systems, 3D information can be visualized by recording and processing 2D elemental images that capture different perspectives of the 3D scene. Recently, 3D imaging for underwater optical communication has been proposed using integral imaging and computational reconstruction. In this technique, an optical signal is encoded using the spread spectrum techniques, and an image sensor array is used to capture the elemental image sequences. The captured information is then processed by multidimensional image reconstruction, followed by a multidimensional correlation to detect the source signal.

In this reporting period, we have investigated a prototype for signal detection in turbid water using 3D polarimetric integral imaging. Polarimetric integral imaging information is captured by using polarization imaging applied to each elemental image before 3D reconstruction. Polarization difference imaging is used to suppresses the partially polarized and unpolarized background noise allowing only the polarized ballistic signal photons to be recorded by the sensor. Polarization difference imaging is useful when the scene contains meaningful polarized signals in the presence of unpolarized or partially polarized noise. In this work, we have used an actively plane-polarized light source, which acts as a polarized optical signal. Furthermore, integral imaging reconstruction is applied to reduce the noise and is followed by a method for detecting and recognizing weakly polarized signals from the noisy images. Multi-dimensional nonlinear correlation is used for the final signal detection. We have shown improved signal detection in degraded conditions with high turbidity levels. Experiments were performed to demonstrate signal detection with 3D polarization difference integral images using multidimensional nonlinear correlation filters. A key benefit of the proposed technique is that the light source can be modulated for robust signal detection, hence enabling imaging through a turbid medium. We show that the 3D polarimetric temporally encoded integral imaging can detect 3D optical signals in a degraded image, even in the presence of turbidity.

Polarization difference imaging can be used to effectively discriminate polarized objects or signals, while conventional imaging cannot be used since it does not measure the polarization content of light. The captured intensity, in principle, can be decomposed into the two orthogonal components of linearly polarized light. This decomposition can be performed by capturing images through an ideal linear polarizer. The intensity distributions obtained at orthogonal linear polarizations are represented by $I_{||}(x, y)$ and by $I_{\perp}(x, y)$ where (x, y) identifies the position on the image and the symbols ‖ and ⊥ represent the two orthogonal directions. In this project, we have used an active polarized light source and transmitted through the turbid water in the presence of non-polarized ambient light; due to this fact, the unpolarized backscattered light is still present in both polarization states. Also, at higher turbidity levels, depolarization of the light source will occur due to scattering, which also contributes to the unpolarized noise present in both polarization states. As the co-polarized image contains polarized signal information and unpolarized noise, the suggested idea is to subtract the opposite-polarized image ($I_{\perp}(x, y)$) from the co-polarized image ($I_{||}(x, y)$) in order to remove depolarized or unpolarized noise present in it. Another advantage of the polarization difference imaging system is the sensitivity of the polarization difference image for small polarized signals in unpolarized noise. Polarization difference signals ($S(x, y)$) are formed as:

$$S(x, y) = I_{||}(x, y) - I_{\perp}(x, y) \quad (1)$$

where $I_{||}(x, y)$ is the co-polarization state image, and $I_{\perp}(x, y)$ is the cross-polarization state image. Polarization difference imaging can enhance the target regions relative to the background image, which helps the correlation-based technique to distinguish the target region. Polarization difference imaging is also proportional to the degree of linear polarization (DLP), defined as $\langle DLP\rangle_{signal} = \langle I_{\parallel} - I_{\perp}\rangle_{signal}/\langle I_{\parallel} + I_{\perp}\rangle_{signal}$. Thus, polarization difference imaging can be used to extract polarimetric information in a scene. The signal $S(x, y)$ is an attenuated signal due to the forward scattering, which results in a weak signal at higher turbidity levels. To improve signal detection under high attenuation, the integral imaging system is combined with the polarization difference imaging for enhancing the detection. Fig. 1 illustrates the flow chart and Fig. 2 illustrates the experimental set up of the proposed multidimensional polarimetric method for underwater signal detection. Figure 3 illustrates the substantial improvements obtained using the proposed method.

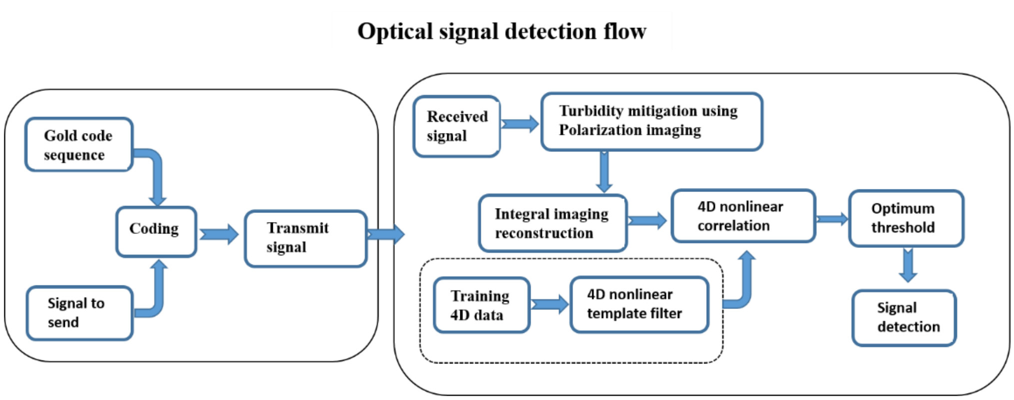

Fig. 1 Flow chart of the proposed 4D nonlinear correlation method for underwater signal detection.

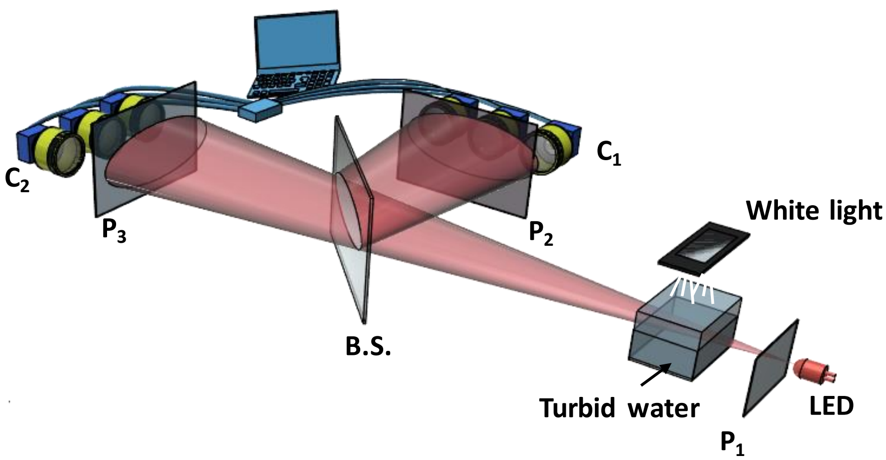

Fig. 2 Experimental setup for a 3D imaging system for underwater signal detection. P1, P2, and P3 polarizer; LED, light-emitting diode; B.S., Beam splitter; C1 and C2, camera arrays.

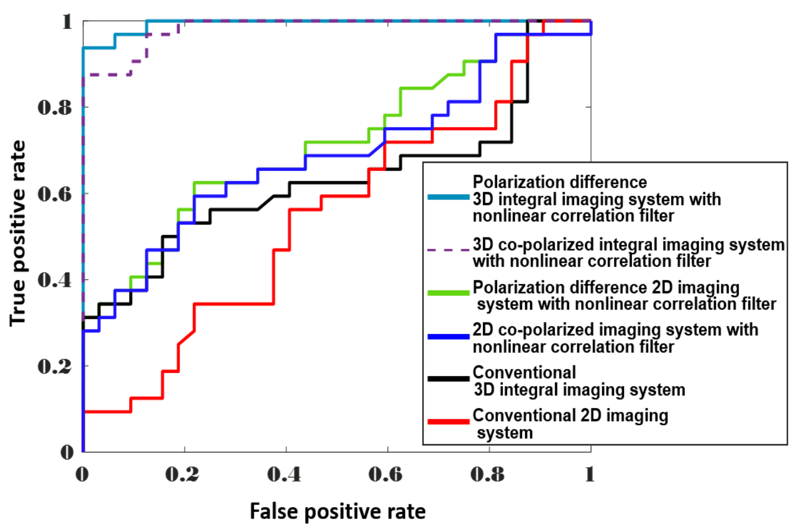

Fig. 3 ROC (Receiver operating characteristic) curves for comparison of different underwater signal detection systems at turbidity level (α=0.117 mm^{-1}). Proposed polarization difference 3D integral imaging system with nonlinear correlation [sky blue solid line] and proposed 3D co-polarization integral imaging system with nonlinear correlation [violate dash line], 2D polarization difference imaging system with nonlinear correlation [green solid line], 2D co-polarization integral imaging system with nonlinear correlation [blue solid line], conventional 3D integral imaging-based system [black solid line], and conventional 2D imaging [red solid line].

In summary, in this project period we have investigated a temporally encoded single-shot polarimetric integral imaging system for underwater signal detection in turbid media. Temporally encoded polarimetric signals are reconstructed and detected by multidimensional integral imaging using 4D nonlinear correlation. The proposed system improves the performance of the underwater signal detection in turbidity in comparison to the conventional temporally encoded 2D and 3D imaging systems. In this period, polarization encoded integral imaging was studied experimentally and evaluated using several performance measurements. The statistical measurements and performance metrics indicate improved performance using our proposed polarimetric integral imaging system as compared to other methodologies considered. The proposed system may be extended in the future for detection in more challenging environments such as underwater turbulence, low light intensity, multipath fading channels, and exploring other integral imaging architectures.

The proposed system is tested at varying turbidity conditions and the performance is measured using the receiver operating characteristic (ROC) curve, the area under the curve (AUC), the number of detection errors as well as by examination of statistical measures such as the Kullback-Leibler Divergence and Bhattacharya distance. The investigations included integral imaging reconstruction procedure, the experimental methods, the correlation based signal detection procedure, the detection based on convolutional neural networks, and the experimental results for underwater signal detection. We have experimentally demonstrated scenarios in which turbidity causes image sensing and detection to fail, while our proposed approach enables successful detection under the same turbidity conditions.

We have continued with experiments to investigate imaging and dedicated algorithms for extracting three-dimensional (3D) information in underwater signal detection in turbidity using deep learning and convolutional neural networks. Additional experiments are in progress to finalize this work.

Please see the publications for more details on what we have accomplished in the past year.

What opportunities for training and professional development did the project provide?

Four PhD graduate students (Timothy O'Connor, Rakesh Joshi, Gokul Krishnan, and Yinuo Huang) worked on this project. A new PhD student (Yinuo Huang, a graduate of UConn) was hired last year to collaborate on this project. One current PhD student (Rakesh Joshi) is performing and leading the experiments in the Lab. Two other existing PhD students [Timothy O'Connor and Gokul Krishnan] help with the investigations. Timothy O'Connor is supported under a GAANN Fellowship from Education Department at no cost to the ONR project.

The students are involved in theoretical, experimental, and numerical simulations in this project. The students work together to build the experimental system, collect data, develop the dedicated algorithms, participate in presentations about the project, write journal and conference papers, etc. The students have attended conferences [online due to COVID-19] to further enhance their education and research experience. This is a cross disciplinary project and there is good interaction between researchers with background in electrical engineering, physics, and mathematics/statistics.

We collaborated with a professor of statistics at UConn to investigate sensing of scattered light with commercially inexpensive compact CMOS image sensors at no cost to this ONR project. We have collaborated with a professor of Physics at University of Barcelona to investigate polarimetric imaging at low light levels at no cost to this ONR project, and professors of computer science at University Jaume I in Spain to investigate faster depth estimation of 3D objects, at no cost to this ONR project.

How were the results disseminated to communities of interest?

The following is a list of publications including journal papers, conference proceedings papers and presentations. These are considered some of the top journals in the field and premiere conferences in optics and photonics, sensing, and imaging, thus the results are widely disseminated.

Journal and Conference Papers:

1. Rakesh Joshi, Gokul Krishnan, Timothy O'Connor, and Bahram Javidi, "Signal detection in turbid water using temporally encoded polarimetric integral imaging," Optics Express, 28, 36033-36045, November 2020.
2. B. Javidi, A. Carnicer, J. Arai, T. Fujii, H. Hua, H. Liao, M. Martínez-corral, F. Pla, A. Stern, L. Waller, Q. H. Wang, G. Wetzstein, M. Yamaguchi, and H. Yamamoto, "Roadmap on 3D integral imaging: sensing, processing, and display," Optics Express, **28**(22), pp. 32266-32293 (October 2020). **Top Download of Optics Express**
3. K. Usmani, G. Krishnan, T. O'Connor, and B. Javidi, "Deep learning polarimetric three-dimensional integral imaging object recognition in adverse environmental conditions," Optics Express, 29 (8), 12215-12228 (April 2021).
4. Vladislav Kravets, Bahram Javidi, and Adrian Stern, "Compressive imaging for defending deep neural networks from adversarial attacks," Optics Letters 46, 1951-1954 (April 2021).
5. T. O'Connor, A. Markman, B. Javidi, "Overview of three-dimensional integral imaging-based object recognition in low illumination conditions with visible range image sensors," SN Applied Sciences, Springer Nature, 2:1724, 2020.
6. Kashif Usmani, Timothy O'Connor, Xin Shen, Pete Marasco, Artur Carnicer, Dipak Dey, and Bahram Javidi, "Three-dimensional polarimetric integral imaging in photon-starved conditions: performance comparison between visible and long wave infrared imaging," Optics Express 28, issue 13, 19281-19294 (June 15, 2020).
7. Gokul Krishnan, Rakesh Joshi, Timothy O'Connor, Filiberto Pla, and Bahram Javidi, "Human Gesture Recognition under Degraded Environments using 3D-Integral Imaging and Deep Learning," Optics Express, 28, #13, 19711-19725 (June 2020). [Top Download of Optics Express]
8. Rakesh Joshi, Bahram Javidi, "Overview of integral imaging-based optical signal detection in turbid water using temporally encoded light sources," OSA Imaging and Applied Optics

Congress, Vancouver, Canada, June 22-26, 2020.

9. Kashif Usmani and Bahram Javidi, "Overview of three-dimensional polarimetric imaging in photon starved conditions," OSA Imaging and Applied Optics Congress, Vancouver, Canada, June 22-26, 2020.
10. T. O'Connor, A. Doblas, and B. Javidi, "Overview of compact and field-portable system for resolution enhanced digital holographic microscopy by structured illumination," OSA Imaging and Applied Optics Congress, Vancouver, Canada, June 22-26, 2020.
11. G. Krishnan, R. Joshi, T. O'Connor, and B. Javidi, "Optical signal detection in turbid water using multidimensional integral imaging with deep learning," to appear in Optics Express, 2021 [November 2021].
12. Kashif Usmani, Timothy O'Connor, and Bahram Javidi, "Three-dimensional polarimetric image restoration in low light with deep residual learning and integral imaging," Optics Express 29 (18), 29505-29517 (August 2021).
13. Gokul Krishnan, Yinuo Huang, Rakesh Joshi, Timothy O'Connor, and Bahram Javidi, "Spatio-temporal continuous gesture recognition under degraded environments: performance comparison between 3D integral imaging (InIm) and RGB-D sensors," Optics Express 29, 30937-30951 (September 2021).
14. Bahram Javidi, Artur Carnicer, Arun Anand, Wen Chen, Pietro Ferraro, J. W. Goodman, Ryoichi Horisaki, Kedar Khare, Malgorzata Kujawinska, Rainer A. Leitgeb, Pierre Marquet, Takanori Nomura, Aydogan Ozcan, "Roadmap on Digital Holography [Invited]," Optics Express 29, 35078-35118 (2021).
15. K. Usmani, G. Krishnan, T. O'Connor, B. Javidi, "Deep learning polarimetric three-dimensional integral imaging object recognition in adverse environmental conditions," Optics Express 29, 12215-12228 (April 2021).
16. Faliu Yi, Ongee Jeong, Inkyu Moon, Bahram Javidi, "Deep Learning Integral Imaging for Three-Dimensional Visualization, Object Detection, and Segmentation," Optics and Lasers in Engineering, Volume 146, 2021.
17. Vladislav Kravets, Bahram Javidi, and Adrian Stern, "Compressive imaging for defending deep neural networks from adversarial attacks," Optics Letters 46 (2021).
18. Rakesh Joshi, Gokul Krishnan, Timothy O'Connor, and Bahram Javidi, "Signal detection in turbid water using temporally encoded polarimetric integral imaging," Optics Express, 28, 2020.
19. B. Javidi, A. Carnicer, J. Arai, T. Fujii, H. Hua, H. Liao, M. Martínez-corral, F. Pla, A. Stern, L. Waller, Q. H. Wang, G. Wetzstein, M. Yamaguchi, and H. Yamamoto, "Roadmap on 3D integral imaging: sensing, processing, and display," Optics Express, 28, (2020).
20. T. O'Connor, A. Markman, B. Javidi, "Overview of three-dimensional integral imaging-based object recognition in low illumination conditions with visible range image sensors," SN Applied Sciences, Springer Nature, 2:1724, 2020.
21. Vladislav Kravets, Bahram Javidi, Adrian Stern, "Defending Deep Neural Networks from Adversarial Attacks on Three-dimensional Images by Compressive Sensing," OSA Imaging and Applied Optics Congress, Vancouver, Canada, July 19-22, 2021. (Invited Paper).
22. Vladislav Kravets, Bahram Javidi, Adrian Stern, "Optical firewall for defending deep neural networks from adversarial attacks," The Optical Society (OSA) and the American Physical Society's Division of Laser Science (DLS), Frontiers in Optics + Laser Science, OSA Annual Meeting, Washington, DC

10/31/2021 - 11/4/2021. (Invited Paper).

23. Pranav Wani, Kashif Usmani, Gokul Krishnan, Timothy O'Connor, Bahram Javidi, "Object Classification in Photon-Starved Conditions using 3D Integral Imaging: Performance Comparison Between Visible and Longwave Infrared Imaging," OSA Imaging and Applied Optics Congress, Vancouver, Canada, July 19-22, 2021.
24. Gokul Krishnan, Rakesh Joshi, Timothy O'Connor, Filiberto Pla, Bahram Javidi, "An overview of hand gesture recognition in degraded environments using three-dimensional integral imaging and deep neural networks," OSA Imaging and Applied Optics Congress, Vancouver, Canada, July 19-22, 2021.
25. Rakesh Joshi, Gokul Krishnan, Timothy O'Connor, Bahram Javidi, "Overview of optical signal detection in turbid water using temporally encoded polarimetric integral imaging," OSA Imaging and Applied Optics Congress, Vancouver, Canada, July 19-22, 2021.
26. Kashif Usmani, Timothy O'Connor, Peter Marasco, Bahram Javidi, "Visible and long-wave infrared imaging in degraded environments using three-dimensional polarimetric integral imaging," OSA Imaging and Applied Optics Congress, Vancouver, Canada, July 19-22, 2021.
27. Rakesh Joshi, Timothy O'Connor, Xin Shen, Michael Wardlaw, and Bahram Javidi, "Optical 4D signal detection in turbid water by multi-dimensional integral imaging using spatially distributed and temporally encoded multiple light sources," Optics Express, 28, pp. 10477-10490, March 2020.
28. Hisaya Hotaka, Timothy O'Connor, Shinji Ohsuka, and Bahram Javidi, "Photon-counting 3D integral imaging with less than a single photon per pixel on average using a statistical model of the EM-CCD camera," Optics Letters, 45(8), 2327-2330 (April 2020).
29. Adam Markman, Timothy O'Connor, Hisaya Hotaka, Shinji Ohsuka, and Bahram Javidi, "Three-dimensional integral imaging in photon starved environments with high sensitivity image sensors," Optics Express, vol. 27, 26355-26368, September 2019.
30. T. Oconnor, A. Anand, and B. Javidi, "Field-portable microsphere-assisted high resolution digital holographic microscopy in compact and 3D-printed Mach-Zehnder Interferometer," OSA Continuum Journal, Vol. 3, No. 4, pp 1013-1020, 15 April 2020.
31. Rakesh Joshi, Bahram Javidi, "Overview of integral imaging-based optical signal detection in turbid water using temporally encoded light sources," OSA Imaging and Applied Optics Congress, Vancouver, Canada, June 22-26, 2020.
32. Rakesh Joshi, Timothy O'Connor, Xin Shen, Michael Wardlaw, Bahram Javidi, "Overview of optical 4D signal detection in turbid water by multi-dimensional integral imaging using spatially distributed and temporally encoded multiple light sources," Three-Dimensional Imaging, Visualization, and Display 2020, Proc. SPIE 11402, 27 April - 1 May 2020.
33. Kashif Usmani and Bahram Javidi, "Overview of three-dimensional polarimetric imaging in photon starved conditions," OSA Imaging and Applied Optics Congress, Vancouver, Canada, June 22-26, 2020.
34. B. Javidi et al., "Multidimensional Integral Imaging for Sensing, Visualization, and Recognition in Degraded Environments," OSA Imaging and Applied Optics Congress, Munich, Germany, June 26-29, 2019. (Invited).
35. Raul Castaneda, Timothy O'Connor, Ana Doblas, Bahram Javidi, "Reduction in data acquisition for resolution improvement in structured illumination digital holographic microscopy," Three-Dimensional Imaging, Visualization, and Display 2020, Conference 11402, 27 April - 1 May 2020.

36. Bahram Javidi, Timothy O'Connor, Arun Anand, Inkyu Moon, and Adam Markman "Automated cell identification with Compact Field Portable 3D optical imaging," SPIE Optical Metrology International Symposium, Munich, Germany, June 24 – 27, 2019. [Keynote Address].
37. B. Javidi, F. Pla, J. M. Sotoca, X. Shen, P. Lattore Carmona, M. Martinez, R. Fernandez, G. Krishnan, "Fundamentals of Automated Human Gesture Recognition using 3D Optical Imaging: A Tutorial," Advances in Optics and Photonics, Volume 12, 2020. Anticipated publication date: September 2020.
38. B. Javidi and A. Markman, "Learning in the dark: 3D object recognition in very low illumination conditions using Convolutional Neural Networks and Integral Imaging," Workshop on Information Optics, Stockholm, Sweden, 1-5 July 2019. (Invited).
39. Bahram Javidi, "Multidimensional Integral Imaging for Sensing, Visualization, and Recognition in Degraded Environments: From Macro to Micro Scales," Workshop on Machine-Learning-Assisted Image Formation, sponsored by French Optical Society (SFO), Institute d'Optique Graduate School (Paris Tech), Savante Francophone Society of Machine Learning, Nice, France, 10-12 Jul 2019.

What do you plan to do during the next reporting period to accomplish the goals and objectives?

This project has been completed. We have conducted experiments according to the tasks and objectives of the proposal on 4D optical signal detection in turbid environments using integral imaging. We have investigated the use of convolutional neural networks and deep learning for the detection of the underwater signal in turbid medium. We have considered improving signal detection and recovery algorithms based on convolutional neural networks and deep learning applied on the captured signals following the 3D reconstruction. We have used 4D correlation on the data for optimal codes such as Pseudorandom and Gold codes for robust signal detection in a turbid environment. We have considered other detection algorithms optimized for communication in multiple noise conditions. In addition, we have used polarimetric sensing and imaging to remove the scattered photons from the detected signal for improved performance. A variety of metrics have been used to measure the system performance in turbid water including receiver operating characteristic curve, number of detection errors, Kullback-Leibler Divergence, Bhattacharya distance, and SNR using the proposed distributed light sources integral imaging-based detection approach. In addition, we have considered approaches to increase the computational efficiency and the speed of signal detection. These include reducing the number of sensors, using a 1-D array of cameras, reducing the number of pixels.

In summary, have performed theoretical, experimental, and numerical simulations for underwater sensing and detection in turbid water, collected data, worked on the development of optimized dedicated algorithms based on convolutional neural networks and deep learning, and submitted journal and conference papers. Further improvements to signal detection in turbid water will be investigated by examining a variety of integral imaging sensing approaches, as well as other optical sensing techniques, signal detection algorithms, and statistical approaches in the ongoing new ONR project.

Honors: What honors or awards were received under this project in this reporting period?

Prizes and Awards

1. *Named by The International Society for Optics and Photonics (SPIE) as a Luminary, August 2021*
2. *Awarded The Optical Society (OSA) Emmett Leith Medal, 2021*

The following papers are Top Download of journals:

B. Javidi, A. Carnicer, J. Arai, T. Fujii, H. Hua, H. Liao, M. Martínez-corral, F. Pla, A. Stern, L. Waller, Q. H. Wang, G. Wetzstein, M. Yamaguchi, and H. Yamamoto, "Roadmap on 3D integral imaging: sensing, processing, and display," Optics Express, **28**(22), pp. 32266-32293 (October 2020). **Top Download of Optics Express**

As of December 2020, the following paper continues to be a Top Download of the Journal of Advances in Optics and Photonics: Manuel Martinez-Corral and Bahram Javidi, "Fundamentals of 3D imaging and displays: A tutorial on integral imaging, Lightfield, and plenoptic systems," Advances in Optics and Photonics, Vol. 10, Issue 3, pp. 512-566, 2018. **Top Download of AOP**

Gokul Krishnan, Rakesh Joshi, Timothy O'Connor, Filiberto Pla, and Bahram Javidi, "Human Gesture Recognition under Degraded Environments using 3D-Integral Imaging and Deep Learning," Optics Express, 28, #13, 19711-19725 (June 2020). **[Top Download of Optics Express]**

Technology Transfer

A Provisional Patent Application has been filed through University of Connecticut on Four-Dimensional Maritime Sensing and Detection System. We have been working with the USPTO to finalize the following application:

SYSTEM AND METHOD FOR OPTICAL SENSING, VISUALIZATION AND DETECTION IN TURBID WATER USING MULTI-DIMENSIONAL INTEGRAL IMAGING

Filed: May 29, 2020
Patent No.: US 11,200,691 B2
Date of Patent: Dec. 14 , 2021