This item is the archived peer-reviewed author-version of:

An optimized planar MIMO array approach to in-air synthetic aperture sonar

Reference:

Kerstens Robin, Laurijssen Dennis, Steckel Jan.- An optimized planar MIMO array approach to in-air synthetic aperture sonar
IEEE Sensors Letters - ISSN 2475-1472 - (2019), p. 1-4
Full text (Publisher's DOI): <https://doi.org/10.1109/LSSENS.2019.2951061>
To cite this reference: <https://hdl.handle.net/10067/1636550151162165141>

An Optimized Planar MIMO Array Approach to In-air Synthetic Aperture Sonar

Robin Kerstens^{*†}, Dennis Laurijssen^{*†}, Jan Steckel^{*†}

^{*}FTI-CoSys Lab, University of Antwerp, Antwerp, Belgium

[†]Flanders Make Strategic Research Centre, Lommel, Belgium

I. INTRODUCTION

Complex in-air sonar sensors capable of scanning the environment in 3D are becoming more popular in industrial environments. This is due to their ability to sense objects in environments where the performance of other sensing modalities suffer. One of the characteristics where this sonar technology still underperforms compared to its alternatives such as lidar, is range and resolution performance [1]. Because sonar makes use of sound waves traveling through air, it is being limited by the medium's attenuation properties (1.318 dB/m at 20 °C and 50% relative humidity for 40 kHz) [2], resulting in very low Signal-to-Noise ratios (SNR) for far-away objects. This makes accurate long-range (10 to 20 m) sensing quite hard with sonar sensors. An intuitive way to counter these issues would be to add elements to the emitter array. This approach would increase the total amount of emitted energy and lead to a greater range and improved SNR. A side-effect is that the array will become focused in a certain direction. Classic signal processing approaches in radar and sonar would then be to use beamforming techniques to steer the emitter array into these specified directions, steering the energy to the areas of interest [3] and scanning the environment one direction at a time. This method of working is not preferred here because of sonar's slow propagation through the air [2]. Since the prototype of the array is using eight emitters (as shown in Fig. 1), it would take a large amount of scans to create an image of the environment. This would make the system inherently slow and unusable in most non-stationary applications such as agricultural robotics or mining. Therefore, this paper takes a look at the methods used in Multiple Input - Multi Output (MIMO) radar and sonar. These systems contain multiple emitters and receivers, where the elements in the emitter array will send out specific signals either separately or simultaneously while the receiver array records all impinging reflections. These methods allow for a greater range and/or resolution to capture smaller details within the field-of-view (FOV) of the sensor [4], [5].

Optimizing these MIMO systems in a mathematically closed form is a complex endeavor, imposing strict constraints on the design parameters of the system. Where, for example, [7],

[8] explain methods to design uniformly distributed arrays, these methods can not be applied in this paper since we are building upon the already existing sensor array of the eRTIS sensor that uses a pseudo-random Poisson-disk placement for its microphones [9]. Therefore, the choice was made to use numeric optimization through a genetic algorithm (GA) that uses a metric in which several key factors of the array's point-spread-function (PSF) are calculated. The exact approach will be explained later on in section II of this paper. Once this emitter array is built it is possible to explore the MIMO techniques of encoded emissions in combination with principles that are inspired on Synthetic Aperture Sonar (SAS), because of the presence of differing known emitter locations compared to the otherwise single emitter of the eRTIS sensor.

SAS is a popular method for underwater imaging where, by dragging a 1D array along a known trajectory and performing measurements at certain intervals, it is possible to mimic a 2D array and gain resolution performance or enhance object recognition capabilities by detecting the shadows that are being cast. This allows systems to scan the seabed and other underwater objects [10], [11]. While most literature regarding SAS focuses on underwater maritime applications [4], [10], [11], this research will aim to use some SAS principles on an in-air sonar sensor used for robotic applications by taking individual measurements at different, calculated, locations in the planar array. These applications have stricter requirements regarding size, as the sensor needs to be easily mountable and is not able to use the entire boat hull, as is the case with underwater SAS.

Fig. 1. The physical prototype of the STSTAB architecture featuring two pseudo-random arrays, one with eight Senscomp 7000 series transducers on the emitter side and one with 32 microphones on the receiving end (the eRTIS [6] emitter is not used).

A previous partly theoretical study for this topic has been done by our research group in [12] but the non-randomized shape of the array causes unwanted side-lobe effects on the emitted pattern (also observed in [11]). Using a mathematical optimization algorithm for the element placement, along with the use of multisine signals (as opposed to commonly used Additive White Gaussian Noise (AWGN) [12]) will lead to a more efficient design with better performance. The structure of the paper is as follows: in section II we will discuss the emitter array and the way the emitter allocation is done by the GA, followed by a comparison of the system using noise and multisine signals and the impact on system performance at the end of section II and experimental results in section III. Section IV is the conclusion of the paper with an overview of future work.

II. SIMULTANEOUS TRANSMIT SAS DESIGN

A. Optimized Transmitter Architecture

When designing an emitter array that is to be used as an imaging sensor certain features are considered important. One of the key characteristics is the PSF, which will indicate how a point reflector is translated into the imaging domain. The aim is to make the PSF as narrow as possible in the main lobe while avoiding artifacts such as grating lobes (or side lobes) that will create false positives. These grating lobes appear when the aperture is sub-sampled in the Nyquist sense [13]. In contrast to [12], where the emitters are positioned in a regular diamond-shape, the emitters in this paper have been positioned by an optimization algorithm that will focus on increasing the peak-to-sidelobe ratio (PSR) and a narrow main lobe width (MLW). The choice to use eight emitters in the prototype is made because of the availability of 8-bit DACs at our research group.

B. Placement Algorithm

The placement algorithm is designed with the help of the MATLAB optimization toolbox. The used fitness function is initially given random X and Y coordinates for every transmitter as input, and calculates parameters such as the PSR and MLW for both the elevation and azimuth, based on the resulting PSF. The calculated PSR and MLW values will be used to calculate a metric and will in turn define the output of the fitness function. Because the transmitter coordinates generated by the algorithm are initially random, a severe penalty is issued when the newly generated coordinates cause the transmitters to overlap or when they are placed outside of the specified region. To speed up the process the algorithm is running in parallel with a population of 200, which is 25 times the number of parameters given to the objective function (eight X-coordinates and eight Y-coordinates). The process is run until the average relative change in the fitness function yields no significant improvements compared to previous generations. The fitness, crossover and mutation functions used are default ones provided by the optimization toolbox (Rank, Heuristic and Adapt Feasible, respectively). As mentioned before, the algorithm will calculate the PSR and MLW based on the PSF of the current proposed array. This means that the algorithm

also keeps in mind the signals and receiver array that are going to be used in this application and so making it a custom fit. These signals are broadband ultrasonic signals ranging from 20 kHz to 100 kHz and are, in PSF calculation as well as in the practical measurements in the next section, combined with the receiver of the CoSys-Lab eRTIS sensor [6]. Fig. 3 shows the operating procedure of the GA. Fig. 2 shows the result used with the current prototype.

Fig. 2. The eight emitter positions as placed by the genetic algorithm. All values are in millimeter with respect to the center point indicated by (0,0). Notice the lack of regular spacing, reducing the array's sidelobes.

Fig. 3. A schematic representation of the genetic algorithm. As a first step, the GA will begin by placing the emitters in a random position (within boundaries, making sure the emitter positions do not overlap. Overlapping will result in a big penalty for the algorithm). It will then calculate the point-spread function (PSF) of the array. The algorithm will then take all the maximum values in both the horizontal and the vertical direction of the PSF and locate the main lobe. When the main lobe is found it will calculate the PSR along with the width of the main lobe. A result with a narrow main lobe and a large PSR will get a good score. The GA will continue to improve the emitter placement as long as significant improvements are being made.

The authors are aware that there are other methods for allocating microphones (or antennas) and emitters in MIMO systems [5], [7], [14], but these are mainly aimed towards Uniform Arrays. Since the existing CoSys-Lab eRTIS microphone array already has a pseudo-random configuration [6], [9] the use of a GA was deemed more efficient.

C. Emission signals

Part of the research in this paper was determining which signals would work best in MIMO sonar. Initially AWGN was used for the excellent properties of its covariance matrix (high auto-correlation and low cross-correlation) when multiple signals are being used [12], [15] (see Fig. 4a). This allows us to transmit simultaneously with multiple emitters and later on separate the different emitter signals when they arrive at the

microphone array at the receiving end. [5], [12]. To restore the original signals in the best way possible it is necessary to find a set of signals with an optimal covariance matrix. There has been extensive research in this field that has led to solutions where signals are being generated or coded with, for example, Kasami sequences or Barker codes [11], [16]. However, when performing real measurements where the eight AWGN signals were modulated with the Barker sequence of length 13, there was no significant observable improvement in the covariance matrix of the overall system. Another study that allows for the use of high bandwidth ultrasonic signals [17] achieves an almost perfect covariance matrix by using a set of frequency modulated signals. The downside in this case is the maximum number of transmitters, being limited to two and so making it unsuitable for the system presented here. Further research on this topic pointed us to the use of multisine signals because their frequency content is much more evenly distributed over the generated frequency spectrum, with a near flat response in the generated band and a steep roll-off in the part of the frequency spectrum where no energy is expected, as illustrated in Fig. 4. Fig. 4b shows that the frequency response of AWGN signals is worse than that of the generated multisine signals, having a less stable response in the generated frequency band and a far less steep roll-off in the higher frequency regions.

To separate the mixed emitter signals impinging on the receiving microphone array, a generalized matched filter is used. The generalized matched filter is based on the Phase Transform (PHAT) maximum likelihood (ML) estimator [18]. The PHAT estimator was chosen for its narrow peak at the point of detection, allowing for a more accurate estimation of the time delay of the wanted signals. In order to obtain optimal results the sensor is calibrated for every angle, as the directivity of the radiation pattern of the emitters will act as a low-pass filter when the measurement angle strays further from the perpendicular direction [19] (also visible for the Senscomp 7000 series transducer in [20]). Fig. 4d shows the difference in performance of the matched filter between the AWGN signal and the multisine signal. In this representation, the amplitude of the deconvolution that is obtained by the matched filter is compared for both signals and the difference compared to the AWGN signals is shown. For the largest part of the angles the maximum value obtained after deconvolution is higher (and therefore the signal is more present) when using multisine signals, which is to be expected because of the higher frequency content mentioned earlier. For these reasons, the multisine signals will be used for the research following this paper.

III. EXPERIMENTAL RESULT

The experimental measurements are done in our lab using the prototype emitter array shown in Fig. 1. The sensors used for this array are the popular Senscomp 7000 series ultrasonic transducers [21] also used in previous research by our research group [12], [20], [22]. This prototype was mounted on a FLIR PTU46 Pan/Tilt head to allow accurate rotation in single degree steps. The emitted signals are then recorded by a Bruel & Kjaer pressure field 1/8" microphone type 4138 and

Fig. 4. a) a comparison of the (normalized) covariance matrices of both simulated AWGN and multisine signals, where multisine achieves a better result. c) also shows this effect where all cross correlation values for both the simulated AWGN and multisine signals are shown in more detail. d) Shows the measured results where one can see that for the greater part of the angles multisine signals obtain higher output values when deconvolving with a matched filter, indicating a better match. In the plot the values of the AWGN signals are being subtracted from both measurements, showing the AWGN measurements as a straight line, showing the difference between measurements more clearly.

conditioned by the Bruel & Kjaer HW 3219 preamplifier. The signals are then sent to a computer running MATLAB using a National Instruments USB-6363 (sampling at 500 kHz). Because the performance and accuracy of the microphone array of the eRTIS sensor is known and has already been established in earlier research [9], this setup allows us to focus on the performance of the newly designed emitter array. Fig. 5 illustrates the performance of the system across the horizontal plane passing through the sensor axis. Even when nearing ± 90 degrees, where almost no signal is present, the system is still capable of receiving and separating the individual emitter patterns, allowing the use of MIMO signal processing. It is also possible to increase the performance of the STSTAB array even more by equipping them with custom designed baffles, spreading their signal more evenly across the frontal hemisphere increasing the FOV of the array [20].

Fig. 5. The matched filter is capable of extracting all eight individual emitter signals (the different colored lines indicate the eight different signals), even at angles nearing ± 90 degrees, displaying the sensor's operation is as expected. The three plots at the top of the figure are zoomed in representations of the maximum values shown in the bottom graph where the maximum values for every angle are shown.

IV. CONCLUSION AND FUTURE WORK

The design of several key features of an accurate MIMO array for in-air sonar sensing has been explored. Using a genetic algorithm, we have optimized the emitter placement of a very broadband in-air MIMO sonar sensor by iteratively calculating its PSF, PSR, and MLW. This method has proven to achieve good results while retaining a fairly intuitive workflow by using an optimization function. The signals that can be used by the sonar array were also studied. The popular AWGN sequences were compared to multisine signals, showing that for deconvolution purposes multisine signals offer better auto-correlation and better cross-channel interference suppression. These claims have been validated using both simulations and real-world measurements. Future work will include practical measurements with the sensor mounted on a robot or vehicle carrying out tasks such as Simultaneous Localization and Mapping (SLAM) and the gathering of point-clouds, combining both emitter and receiver array to illustrate the real-world imaging improvements brought by this sensing approach, and further exploring the possibilities for broadband ultrasound emission signals with suitable auto-correlation and cross correlation characteristics. Building on the SAS principles it is also interesting to study the shadowing effects and see whether this can be useful with a compact 2D emitter array of this size.

REFERENCES

- [1] O. Siciliano, B. and Khatib. *Springer Handbook of Robotics*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008.
- [2] A.D. Pierce. *Acoustics: An Introduction to Its Physical Principles and Applications*. Acoustical Society of America, 1989.
- [3] B.D. Van Veen and K.M. Buckley. Beamforming: a versatile approach to spatial filtering. *IEEE ASSP Magazine*, 5(2):4–24, apr 1988.
- [4] Yan Pailhas, Yvan Petillot, Keith Brown, and Bernard Mulgrew. Spatially Distributed MIMO Sonar Systems: Principles and Capabilities. *IEEE Journal of Oceanic Engineering*, 42(3):738–751, 2017.
- [5] Jian Li and Petre Stoica. *MIMO Radar Signal Processing*. John Wiley & Sons, Inc., Hoboken, NJ, USA, oct 2008.
- [6] Jan Steckel. "Embedded Real Time Imaging Sonar" <https://www.3Dsonar.eu>, 2019.
- [7] A A Gorji, T Kirubarajan, and R Tharmarasa. Antenna allocation for MIMO radars with collocated antennas. *Information Fusion (FUSION), 2012 15th International Conference on*, pages 424–431, 2012.
- [8] Jian Li, Petre Stoica, and Xiayu Zheng. Signal synthesis and receiver design for MIMO radar imaging. *IEEE Transactions on Signal Processing*, 56(8 II):3959–3968, 2008.
- [9] Robin Kerstens, Dennis Laurijssen, and Jan Steckel. eRTIS: A Fully Embedded Real Time 3D Imaging Sonar Sensor for Robotic Applications. In *2019 International Conference on Robotics and Automation (ICRA)*, volume to be publ, pages 1438–1443. IEEE, may 2019.
- [10] Michael P Hayes, Peter T Gough, and Senior Member. Synthetic Aperture Sonar A Review of Current Status 05191242.pdf. 34(3):207–224, 2009.
- [11] Bo Wei, Tian Zhou, Haisen Li, Tianyao Xing, and Yixuan Li. Theoretical and experimental study on multibeam synthetic aperture sonar. *The Journal of the Acoustical Society of America*, 145(5):3177–3189, may 2019.
- [12] Jan Steckel. Sonar system combining an emitter array with a sparse receiver array for air-coupled applications. *IEEE Sensors Journal*, 15(6):3446–3452, 2015.
- [13] H L Van Trees. Optimum Waveform Estimation. In *Optimum Array Processing*, pages 428–709. John Wiley & Sons, Inc., New York, USA, 2002.
- [14] Jian Li and Petre Stoica. MIMO Radar with Collocated Antennas. *IEEE Signal Processing Magazine*, 24(5):106–114, sep 2007.
- [15] Enrique García, José A. Paredes, Fernando J. Álvarez, M. Carmen Pérez, and Juan Jesús García. Spreading sequences in active sensing: A review. *Signal Processing*, 106:88–105, 2015.
- [16] Ana Jimenez Martin, Alvaro Hernandez Alonso, Daniel Ruiz, Isaac Gude, Carlos De Marziani, Maria Carmen Perez, Fernando J. Alvarez, Cesar Gutierrez, and Jesus Urena. EMFi-Based Ultrasonic Sensory Array for 3D Localization of Reflectors Using Positioning Algorithms. *IEEE Sensors Journal*, 15(5):2951–2962, may 2015.
- [17] Qiu Hua Tian. Analysis and Design of Multiple-input Multiple-output Synthetic Aperture Sonar Systems. Master's thesis, University of Toronto, 2015.
- [18] C. Knapp and G. Carter. The generalized correlation method for estimation of time delay. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 24(4):320–327, aug 1976.
- [19] Hannes Elmer and Herbert Schweinzer. High resolution ultrasonic distance measurement in air using coded signals. In *IMTC/2002. Proceedings of the 19th IEEE Instrumentation and Measurement Technology Conference (IEEE Cat. No.00CH37276)*, volume 2, pages 1565–1570. IEEE, 2002.
- [20] Robin Kerstens, Dennis Laurijssen, Walter Daems, and Jan Steckel. Widening the Directivity Patterns of Ultrasound Transducers Using 3-D-Printed Baffles. *IEEE Sensors Journal*, 17(5):1454–1462, 2017.
- [21] Senscomp. Series 7000 Ultrasonic Sensor Datasheet. (734):1–3, 2014.
- [22] Jan Steckel, Andre Boen, and Herbert Peremans. Broadband 3-D sonar system using a sparse array for indoor navigation. *IEEE Transactions on Robotics*, 29(1):161–171, 2013.