Sensor Signal Processing for Defence Conference

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DIRECTION OF ARRIVAL ESTIMATION USING A CLUSTER OF BEAMS IN A CONE-SHAPED DIGITAL ARRAY RADAR

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Outline

- System description and potentialities
- PAR vs DAR with conical array
- Aim of the study
- Proposed direction of arrival estimation technique
- Cramer Rao lower Bound derivation for elevation direction of arrival estimation
- Cramer Rao lower Bound comparison
- Beam cluster tilt
- Conclusions
Innovative architecture for masts to be mounted on ships “d.Mast”, which is being studied and demonstrated by Fincantieri S.p.A. and Seastema S.p.A.

N available resources

Conical geometry

Shared services

X-band Radar is one of the available resources
The RX array is modelled as the “d.Radar”

Conical array whose horizontal sections have the same number of radiating elements.

Approximate dimensions

- Larger diameter less than 1.5 m
- Height less than 1 m

AD conversion at element level.
Circular array & number of radiating elements

- The circular shape of the array allows to spare radiating element

- Rule of thumb

\[
\Delta N_{el} = \frac{N_{el}(circ)}{N_{el}(square)} = \frac{2\pi r \cos(\phi_0)}{4L} \frac{4 \sin(\alpha_0/2)}{\pi}
\]

Compare performance of the different array configurations in the worst case \((\delta\phi_{SQ-max})\)
Circular array & 3D angular scan/coverage

- 360° azimuth beamforming without beamscanning, only shifting of the sector of active elements
  
  ↓

  Beams have the same width in azimuth whichever the steering direction is!

- Coverage in elevation with traditional beamforming.
Array of radiating elements to form multiple beams with different characteristics and functionalities

- **Phased Array Radar (PAR)**
  - Analog BeamForming (ABF) through beamforming networks
  - fixed number of beams
  - pre-determined beam characteristics

- **Digital Array Radar (DAR)**
  - Early analog to digital (AD) conversion at and recording of all the amount of data for successive centralized processing
  - “Ubiquitous radar”
  - reduction of the dynamic range and isolation requirements
  - Natural solution with circular array

**DAR provides flexibility at the expense of increased computational load and data transfer rate**

advanced processing schemes are required to improve efficiency
**Digital vs Phased Array Radar (I)**

### Phased Array
- Fixed number of beams (BFN)
- Beam shape is fixed at design time
- RX beam are necessarily always present for:
  - Detection
  - DoA estimation (otherwise DoA of detection must be illuminated again)

### Digital Array
- Fixed number of beams given by the maximum available computational load
- It is possible to synthesize virtually any desired beam by storing the data collected at the element level
- It is possible to modify beams adaptively depending on data content
- $\Delta$ monopulse beams can be evaluated only for the «range cells» where a target has been detected

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"Direction of arrival estimation using a cluster of beams in a cone-shaped digital array radar"
Digital vs Phased Array Radar (II)

**Digital Array**
- Few beams are used for the search
- It is possible to add beams in «critical» regions, use multiple tilts to handle clutter, etc...
- A lot of computation capability is left for accurate DoA estimation, corrections, etc..

**Phased Array**
- Beam cluster with preassigned shape
- Flexibility in the use of multiple beams

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Digital vs Phased Array Radar (III)

Stima DOA interferenti CW (i.e. standoff jammer)
- Inhibit TX for a some PRTs and collect responses
- How many times TX must be inhibited to know the whole intereferece scenario?

Phased Array
- For each inhibited TX, a few DoAs are surveyed, covered by the available RX beam cluster
- Many inhibited PRTs are necessary to cover all angles

Digital Array
- With a single inhibited PRT data from all DoAs are collected
- Then beams in all directions can be synthesized in background

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Digital vs Phased Array Radar (IV)

**Phased Array**
- Performance depends on the used beam cluster
- Beam cluster optimisation to cancel MB jammer and estimate target DoA

**Digital Array**
- After jammer DoA estimation, it is possible to build a beam steered to it
- Close-to-ideal performance achievable
- Use of single auxiliary beam to cancel jammer – reduced adaptivity losses

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**CW interference nulling (i.e. standoff jammer)**
- Beam cluster use

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Aim of the study

Starting point: innovative conformal DAR system

Numerous potentialities

Analysis of an approach for Direction of Arrival (DoA) estimation based on a properly designed crowded cluster of RX beams and comparison with traditional monopulse approach
PAR vs DAR multiple beam forming

- Typical cluster of beams in PAR:
  - for each azimuthal direction and range
    \[ N_\Sigma \] sum beams, \( N_\Delta \) difference beams
    + 1 omnidirectional beam.

- Possible strategies in DAR:
  
  **Detection:**
  - for each azimuthal direction
    \[ N_\Sigma \] sum beams.

  **DoA estimation:**
  - only at DoA and ranges where detections occurred
    - \( N_\Delta \) difference beams.
    - Cluster of crowded sum beams
Detection Beam Cluster for DAR

 Beam cluster configuration for radar operating in search mode with low steering direction in elevation (5°).

- Solid lines: sum beams with a width of 2.6° in elevation and 2° in azimuth to cover an aperture of nearly 8° in the elevation dimension.
- Dashed lines: difference beams for DoA estimation.
Low elevation angles problem (I)

Operational scenario $\rightarrow$ signals from a low altitude target are received through a direct and a specular reflected path in the flat earth model.

\[
\begin{align*}
\theta_T & = \text{angle of arrival of direct signal} \\
\theta_M & = \text{angle of arrival of specular reflected signal} \\
D & = \text{baseline distance} \\
H_{tgt} & = \text{height of target} \\
H_{ant} & = \text{height of antenna}
\end{align*}
\]
Lower Sum and especially Difference beams in the cluster may suffer from multipath arising from low-height target.

Possibility of using a different approach for DoA estimation, in particular for the elevation angle.
Presented DoA estimation for DAR

- Data acquired by all elements are available at a central processing unit before beamforming.

- Identification of the beams and resolution cells detections occurred.

  Only for those detections a crowded clusters of sum beams properly displaced in the angular area of interest must be formed for accurate angle estimation.

- Use of a wide beam cluster

  even a high number of beams is possible for the few detected targets

  Computational cost is certainly low
CRLB derivation for elevation DoA estimation

- Received signal
  \[ x(\theta) = A_0 G_{TX}(\theta, \theta_0) G_E(\theta) T_s(\theta) + T_n \]

- Probability density function
  \[ f[x] = \frac{1}{2\pi \cdot \det(M)} \exp\left\{ -\left[ x - A_0 v \right]^H M^{-1} \left[ x - A_0 v \right] \right\} \]

- Elevation DoA estimation accuracy
  \[ \sigma_\theta^2 = 2 \left( \frac{|A_0|^2}{\sigma_n^2} \right) \dot{v}^H \left[ M^{-1} - \frac{M^{-1} v v^H M^{-1}}{v^H M^{-1} v} \right] \dot{v} \]
Comparison between the accuracies of monopulse (3Σ+3Δ) and estimation of elevation DoA through a cluster of K beams equally spaced in an aperture of 8°.

- **Sum beams**
  modified Taylor windows both in azimuth PSLR of 42 dB and elevation PSLR of 36 dB.

- **Difference beams (elevation)**
  Bayliss taper with same PSLR.

- **SNR_{el} = -20 dB**
  → peak SNR on the central beam of nearly 13 dB.

Performance equivalence, especially in the interval [-4°, 4°]
CRLB comparison (II)

Impact of transmit pattern

Omnidirectional TX pattern and elements

Directive TX pattern and omnidirectional elements

\( \theta_T = 5^\circ \)

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The steering direction of the lower beam in the cluster is selected.

The steering direction of the remaining beams in the cluster follow it, to uniformly cover the 8° angular aperture.

AIM: provide a gain of at least $X$ dB to the direct signal from $\theta$ with respect to the multipath signal received from $\theta_M$

under worst condition of operation (minimum target height)
Example: provide a gain of at least 3 dB to the direct signal from $\theta$ with respect to the multipath signal received from $\theta_M$.

$H_{tgt}=30 \text{ m}, (\theta-\theta_M=0.17189^\circ)$

loss of -17 dB in the target direction for $H_{tgt}=30 \text{ m}$
The design becomes less demanding as the target height increases with a loss of -7 dB in the target direction for $H_{tgt}=60$ m and -17 dB for $H_{tgt}=30$ m.
Conclusions

- An innovative conformal DAR has been presented (conical shape factor) with its potentialities and some comparison to more usual PAR.

- We derived the theoretical expression of the CRLB for elevation angle estimation using a cluster of beams.

- We analysed the limit performance of DoA estimation achievable with monopulse to those achievable with a RX beam cluster solution that is shown to be more attractive for DAR.

- Performance of both techniques resulted to be comparable, making the second particularly interesting for those situations where monopulse is known to experience performance degradation, as low elevation angle estimation.

- In this latter case an example of the design of the cluster of beams in presence of specular multipath has been provided.
Approximate knowledge of the jammer DoA

- Antenna nulling without fast time adaptivity
  - The beam pattern is formed with a null in the known jammer direction without estimating and inverting the disturbance covariance matrix.
  - The accuracy of the knowledge of the jammer DoA has an impact on the achievable Signal to Interference and Noise Ratio (SINR).
  - In the proposed example, the beam steering direction is set to $(15^\circ, 0^\circ)$ in elevation and azimuth, and the jammer DoA is $(17.5^\circ, 0^\circ)$ and the Jammer to Noise Ratio (JNR) is set to 30 dB.
  - The cancellation performance rapidly degrades as the jammer DoA inaccuracy increases.

![Graph showing SINR vs. error percentage of elevation beamwidth.](image-url)
Approximate knowledge of the jammer DoA

- **Antenna nulling with fast time adaptivity at beam level**

  - The adaptive beam pattern is formed from a cluster of beams: $N_x + 1$ steered in the estimated jammer direction.

  - The covariance matrix to be estimated at beam level has a reduced dimension, still allowing to recover a near ideal performance.

  - Steering direction is set to $(15^\circ, 0^\circ)$ in elevation and azimuth and the jammer DoA is $(16^\circ, -1.5^\circ)$
Jammer DoA not known

- **Antenna nulling with fast time adaptivity at beam level**
  - The adaptive beam pattern is formed from a cluster of sufficient number beams to cover the target and jammer area.
  - The covariance matrix to be estimated at beam level has a higher dimension.
  - Steering direction is set to \((15^\circ, 0^\circ)\) in elevation and azimuth and the jammer DoA is \((16^\circ, -1.5^\circ)\)

![Diagram showing cluster, jammer area, target area, and adaptive pattern.]

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