Cognitive Radars (CRs) Could Improve Target Engagement Success Rate

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Abstract— **Based on information available on Cognitive Radar (CR) technologies, one can anticipate their potential impact on target track quality that may improve target engagement success rate. CR could multiply force capabilities to respond to threats posed by nefarious groups using advanced technologies against our nations and our allies. However, so far there seems to be no CR technologies currently deployed on military platforms or for military applications but there are indications that some are in development. In the future, CR is expected to offer the capability to detect and track small targets (or stealth platforms) over much extended range than current radar under the same conditions. It could contribute to enabling a drone to disable an opposing force platform or to eliminate drones representing threats to civilian aircraft.**

Keywords-cognition; radar; target engagement; success rate.

I. INTRODUCTION

This paper is based on research done by the author [1] for the Defence Research and Development Canada (DRDC) Science and Technology Outlook function to address the following question: What are cognitive radar (CRs), their technology enablers, their applications and their implications on the Defence and Security (D&S) domains and systems? In addition, a method for assessing target engagement success rate will be summarised and used to illustrate the potential advantage of CR over traditional radar.

The concepts of CRs were developed in the 90s. Haykin's initial thoughts about radar cognition can be found in his 1990 paper [2]: "…we have coined the term radar vision. The goal here is to make radar an intelligent remote sensing device, such that it is capable of developing cognition of the surrounding environment." Later he expanded these CR concepts in several seminal papers [3][4]. Activities under the Defence Advanced Research Project Agency (DARPA) addressed the development of CRs with similar concepts starting from a Knowledge-Based (KB) system point of view with the work led by Guerci who reported in 2014 on Cognitive Fully Adaptive Radar (CoFAR), which was tested in a real environment: "A new and fully adaptive environmentally aware (cognitive) radar and signal processing architecture is introduced to meet the challenges of increasingly complex operating environments" [5]. CoFAR uses a radar centric Sense-Learn-Adapt (SLA) approach based on an 'observe, orient, predict, decide and act' (OOPDA) loop from cybernetics [6][7] well known to Command and Control (C^2) where the learn part is a Knowledge-Aided (KA) expert system with supervised training. While becoming environmentally aware, a cognitive system develops some self-awareness of its purpose (metacognitive or introspective capacity) [8]. DARPA and sibling defence organizations offer perspective extending academic works into higher level of technology readiness. They report on radar system development and publish results from trials in real environments.

Section II presents the evolution of radar technologies from adaptive to cognitive ones. Section III relates to examples of applications. Section IV provides some of the claimed performance. Section V presents a method to evaluate the trend of CRs in improving target engagement success rate. Section VI offers comments on work in progress. Section VII provides a summary of findings.

II. FROM ADAPTIVE TO COGNITIVE RADAR

Basic radar transmits a signal via an antenna to illuminate a scene. That signal bounces back from scene objects to the same antenna (monostatic) which feeds the receiver. Processing of signal echoes allows performing a variety of measurements such as location, velocity and trajectory. A Traditional Active Radar (TAR) offers some adaptive capabilities compared to basic radar. TAR was improved with adaptive receiver processing, beamforming, and constant false alarm rate. Basic radar and TAR heavily relied on the cognitive abilities of their expert operators to select, for example, waveforms and time duration on an observation area where a target was suspected to be. CRs provide some of these cognitive abilities through a learning process using statistical methods and retention of information from previous observations. A first step toward CR capabilities, besides what experienced operators could perform, was achieved by adding feedback from the receiver to the transmitter, as described in [9]. This closed-loop feedback control radar system or fully adaptive radar was labelled Fore-Active Radar (FAR) by Haykin [10]. FARs are advanced radar systems with feedback loops between fully adaptive receivers and adaptive transmitters including antenna beamforming [10] as illustrated in Figure 1.

There is no unambiguous definition of CR. Guerci [5] proposed a practical definition as follows: CR "is a system that is capable of sensing, learning, and adapting to complex situations with performance approaching or exceeding that achievable by a Subject Matter Expert (SME), especially for real time operations which demand automation."

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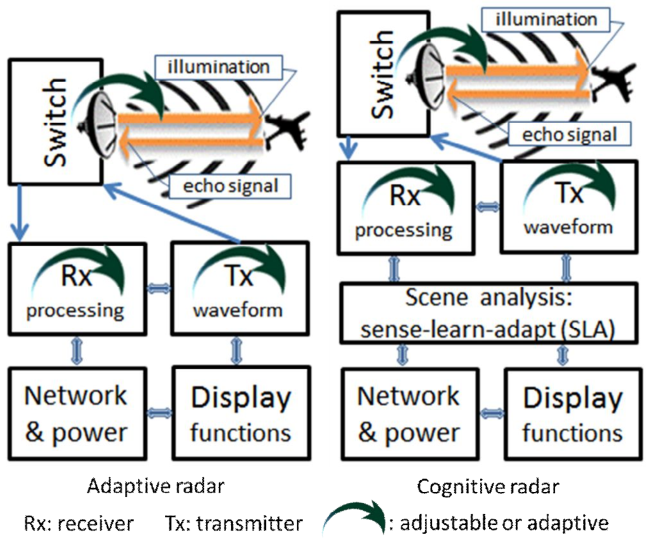

Figure 1. Simplified diagrams of adaptive and cognitive radars.

Figure 1 provides a simplified block diagram of a CR adopting SLA as one block. Haykin [10] stated that: CR "differs from TAR as well as FAR by virtue of the following capability: the development of rules of behavior in a self-organized manner through a process called learning from experience that results from continued interactions with the environment."

"The key idea behind this new paradigm is to mimic the human brain as well as that of other mammals with echolocation capabilities (bats, dolphins, whales, etc.)" [11]. This overarching principle of a CR was inspired by the ability of bats and dolphins to track and home in on their prey. "There is much that we can learn from the echo-location system of a bat" [4]. The principle was extended keeping in mind that useful CR is expected to track multiple targets [12]. In addition, long-range detection may require different strategies or principles than biologically inspired homing in on a close target optimisation techniques.

In his 2006 CR paper [9], Haykin proposed a CR target-tracking system that continuously learned about the environment, intelligently adjusted the transmitter, and incorporated receiver-to-transmitter feedback.

In general we can say that adaptive systems react to their environment using predefined rules, but cognitive ones can develop new rules in real time with or without supervision.

Cognitive systems designed to reach users' goals use different machine learning techniques and memory retention to:

1. address immediate reaction types (parasensory and premotor);
2. plan tactics (complex and abstract information of perceptual or executive character); or
3. change strategy toward goals (dynamics of the perception–action cycle in sequential behaviour and reasoning).

A CR can learn from the observed effects from stimuli that the CR designed and generated. It can create new algorithms based on observations of its manipulation of the environment. CRs are proactive (anticipative or predictive) while TARs are responsive—they wait until something happens. CRs probe the environment to see what happens if they transmit a signal with a given waveform or pulse shape.

A. *Enabling Technologies*

CR shares technology enablers with TAR, Phased-Array Radar (PAR) systems and Digital-Array Radar (DAR) [13], these include Software Defined Radios (SDRs), SDR Sensors (SDRSs) [14], software defined radar [15], field-programmable gate arrays (FPGAs), Graphics Processing Units (GPUs), cell phone Application Specific Integrated Circuits (ASICs) and Digital Signal Processors (DSPs) [16]. These common enablers include an evolution to modern phased array architectures [17] from Passive Electronically Scanned Array (PESA) to Active Electronically Scanned Array (AESA). AESAs have been deployed in missile, fighter aircraft, surveillance platforms, drones and air defence systems. AESAs' Transmit/Receive Modules (TRMs) for each antenna element, or group of antennas, enable them to accomplish multiple functions simultaneously such as radio communications, cellphones, jamming and multi pencil beams.

B. *Evolution*

Interestingly, "The continued 'digitization' of radar front-ends and resultant TRM flexibility, coupled with advances in advanced KA high performance embedded computing have afforded a unique opportunity for a leap-ahead capability in a radar's ability to adapt to complex target-environment scenarios...from the nascent field of cognitive radar" [18]. One also notes impressive capabilities such as "Deep learning cognitive radar for Micro Unmanned Aircraft Systems (UAS) detection and classification," Mendis (2017) [19] showed the exceptional capabilities of this type of cognitive radar to distinguish between very small drones at relatively low signal to noise ratios. Used of a strategy to select waveforms, as for the airborne CARABAS radar, to provide good resolution to distinguish targets [20][21] at short ranges [22][23], and High Frequency (HF) Over-The-Horizon (OTH) radar by dynamically selecting frequencies and waveforms in response to sensed spectrum occupancy [23][24] and ionospheric conditions, approach cognitive radar [23][25] but lack SLA ability to design new strategies.

III. EXAMPLES OF APPLICATION

Cognitive Radar Information Networks (CRINs) were proposed in [26] to secure large, unmanned borders such as the 3,700 km Canada/U.S. border that runs through the Great Lakes. Border security represents a major challenge given the limited sensor capabilities to cover continuously the various ships and platforms crossing in such large areas. Using cognitive sensors and radars in a network of collaborative systems could be a sensible approach to enhance risk mitigation and for reducing operator overload.

CRIN and CR should be considered as a source of inspiration in studies for updating the North Warning System

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(NWS) to provide support for North American Aerospace Defense Command (NORAD) aerospace warning and control missions for insuring a continuous coverage of the air and maritime approaches to and within North America. Currently DRDC is investigating the value of adding some cognitive capabilities to our military radar systems.

IV. CR Claimed Performances

In the unclassified domain one can find several CR test results from simulations and a few experiments in real environment scenes. In general the results obtained show significant improvements in all the parameters radar systems can provide about a target such as position, trajectory, velocity, acceleration, distance, altitude, jet engine modulation, and early target detection. In most operational scenarios, providing early accurate positional information is critical [27]. Reported experimental results show that CR outperformed TAR by at least one order of magnitude when using the same signal processing performance metric [10]. In a real environment using a CoFAR, [5] reports a 10 to 15 dB Signal-to-Interference-plus-Noise Ratio (SINR) for Moving Target Indicator (MTI) improvement against non-homogenous clutter. This means that the reported results show some evidence that CR significantly outperforms TAR in the situations described.

Several advantages of CR over TAR, when using the same signal processing technique, were reported in [28], e.g., to reach a Root-Mean-Square Error (RMSE) of the velocity of about 7.5 m/s, CR took 0.17 s and TAR 2.4 s, which is more than one order of magnitude faster.

The cumulated evidence from CR publications allows inferring that a substantial advantage can be gained by adopting new military CR technologies against current and emerging threats, e.g., such advanced capabilities could better defeat threats from low cost emerging technologies for Cognitive Electronic Warfare (CEW) and weaponized drones.

Assuming that CRs could rapidly change their modulation or transmitting schemes, it may make such radar signal difficult to jam with legacy jamming techniques. If advanced CRs use noise-like signal and radiation patterns with a high degree of unpredictability, they would be more difficult to jam even with CEW.

When compared to TARj with similar antenna performance, there are specific advantages that could be attributed to CRs such as:

1. Extend detection range [28].
2. Shorten the time to acquisition in target tracking [29].
3. Improve the accuracy of positional information of tracked targets [30].
4. Reduce risk in selecting an intelligent choice of decision-making mechanism in the transmitter for a prescribed goal of interest when confronted with environmental uncertainties and disturbances in real time [31].
5. Offer the agility necessary to defeat 'Digital Radio Frequency Memory' based jammer/spoofing technology which essentially captures the transmitted signal and reradiates it towards the radar receiver, typically with some delay or modulation attached [31][32].
6. Detect smaller radar cross section (RCS) targets such as drones and stealth platforms [33].
7. Increase capabilities of passive radar and multistatic radar systems which could detect some stealth aircraft better than conventional monostatic radars, since first-generation stealth technology (such as the F-117) reflects energy away from the transmitter's line of sight, effectively increasing RCS in other directions, which multistatic passive radars can monitor [20].
8. Increase the likelihood of defeating standard electronic warfare and CEW by unexpectedly and rapidly changing waveform characteristics [31].
9. Use difficult to detect waveforms including wideband signals, limit opposing force opportunities to use or trigger their electronic countermeasures to reduce a potential range advantage a radar system may offer in targeting opposing force assets or platforms [32].
10. Reduce the susceptibility (lower likelihood) of being fooled by artificial coherent target energy, including decoys [31].
11. Use built-in shielding against misdirecting/degrading Direction-of-Arrival (DOA) measurements [31].
12. Offer enhanced geolocalization by networked CRs [31][34].
13. Deliver faster high precision information about targets [5][28].
14. Can contribute to communications when other means are jammed [34].

V. Potential Impact of CR on Target Engagement Success Rate

Cybernetic models were used in analyzing coalition live and simulated exercises. These cybernetic models allowed simulating the decision-making processes made by operators at command centers including:

1. monitor the situation;
2. assess the situation and estimate adversarial intent;
3. develop alternative Courses-Of-Action (COAs);
4. predict consequences for both sides (own and opposing forces);
5. decide a COA; and
6. direct the COA execution while monitoring an evolving situation in the environment (repeat 1 to 6).

By using cybernetic models to interpret data and information collected during experiments, one can process and evaluate the stages through a set of Measures Of Performance (MOPs). Similarly, Measures Of Effectiveness (MOEs) can provide an assessment of the resulting degree of mission accomplishment in scenarios to scale MOPs relatively to MOEs, i.e., asserting both that the system performs its tasks well and that those are the correct tasks.

When running these cybernetic models over data collected from a large number of trials, one obtains a graph like the one depicted in Figure 2 relating interception success rate as a function of system time delay and track data accuracy and their timeliness. From these trials, the main delay was due to the human in the loop and imposed

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transmission timing. However, track data timeliness and accuracy were also affecting target interception success rate. If legacy radars are replaced by CRs delivering more accurate data with less delay, one can infer from Figure 2 an increase in target interception success rate.

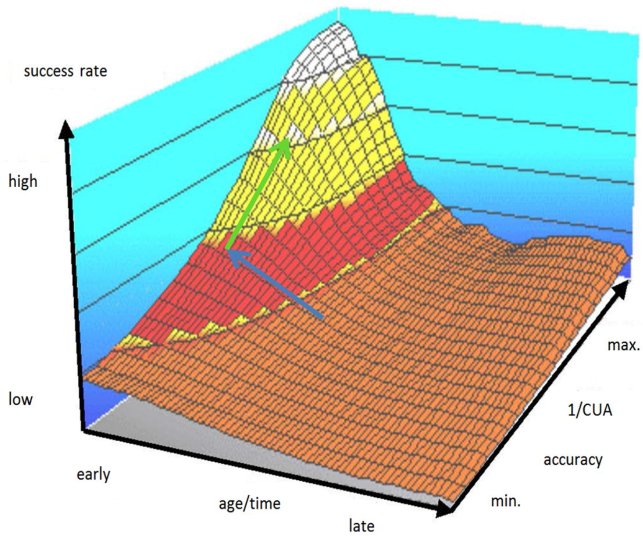

Figure 2. Potential mission success rate as function of input information age and accuracy (inverse of Circular Uncertainty Area, CUA) for a fixed effector's strategy [35].

A possible interpretation of Figure 2 is that track data in the red area and below are not appropriate for targeting with a specific effector. If a given CR track is delivered to this effector ten times earlier (blue arrow) than from a TAR and that the accuracy is several times better (green arrow), then this track data may reach the yellow/white area where it might be considered of "targeting grade". That is, this engagement has a higher likelihood of success.

In [36][37], we posited that with the advent of cognitive networks, sensors, and shooters, it seems more achievable today to accelerate and improve the sensor-to-shooter loop with a high likelihood of lower fratricide, lower collateral damage, and precise effects on intended targets or end state.

VI. Multistatic Multiband Complexity Adds Capabilities

Recently the author identified some new aspects of cognitive radar when adding other dimensions such as multistatic, multiband and the agility offered by the AESA approach in order to reduce the infrastructure of antennas on a platform (ship or aircraft). Platform Radio Frequency (RF) systems to provide radar, communications and Electronic Warfare (EW) functions are evolving towards an integrated system approach know as MultiFunction RF (MFRF) systems [38]. This adds some complexity to the systems but offers several advantages in trying to defeat new threats such as stealth aircraft and hypervelocity cruise missiles.

The hypothesis is how much is feasible and advantageous to build a Cognitive-Multistatic-Multiband-Radar Network (CMMRN)?

Essentially, a CMMRN is a system made of interconnected radar systems with the following capabilities:

A. *Multistatic*

Monostatic radar uses one antenna for transmitting a signal illuminating a scene that may include a target and uses the same antenna for receiving reflections of the signal. Multistatic radar uses at least either two transmitting or two receiving antennas, providing multistatic beam angles between the illuminating signal(s) and the reflected ones. When these beam angles are sufficiently large, such complex radar configurations are outweighed by the potential advantages of early detection of cruise missiles and stealth platforms, which increases the likelihood of successfully intercepting incoming threats [39]. Different types of multistatic radar systems exist: active and passive [40]. Passive radar uses transmitters of opportunity while active radar uses own transmitter. Currently, transmitters of opportunity are not available in Canadian Air Defense Identification Zone (CADIZ), which includes the entire Canada's Arctic Archipelago as part of the overall North American Aerospace Defense Command (NORAD) modernization, aka, Evolution of North American Defense (EvoNAD). This CADIZ is substantially extended from the previous CADIZ of the North Warning System (NWS). The modernization of the NWS not only needs to address this extended area but the range of potential threats to the continent which are more complex and increasingly difficult to detect, such as threats posed by adversarial cruise missiles and new ballistic missiles. However, with the advent of new Low-Earth-Orbit (LEO) satellite constellations, new transmitters of opportunity [41] illuminating Canadian Arctic are becoming a reality to consider.

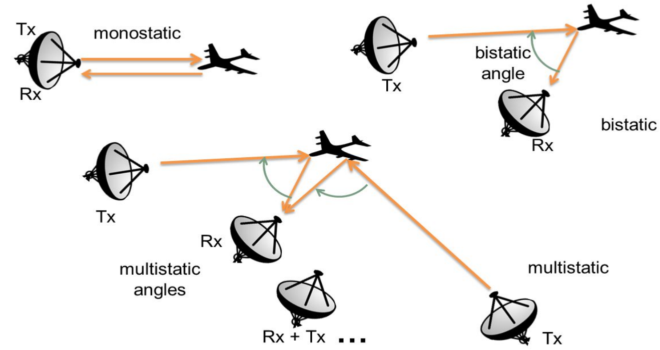

Figure 3. Monostatic, bistatic and multistatic radar systems.

B. *Multiband*

Radar operating in one band offers advantages and disadvantages specific to that band. A multiband radar may optimally combine advantages from operating in several bands for predefined operational goals, e.g., using the S-band for its strong immunity against weather clutter and good detection range, X-band to generate narrower beams for target tracking and improving spatial resolution, and VHF for extended range and its abilities to detect stealth targets. Multiband radar systems allow enhancing target

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classification and detection, and exploiting multispectral imaging of complex targets [42].

C. AESA of New Military Radars

AESAs' Transmit/Receive Modules (TRMs) for each antenna element or group of antennas enable them to accomplish multiple functions simultaneously such as radio communications and multi-pencil beams. TRMs decrease the total energy demand, provide linearity and reduce nearby spectrum pollution from non-linearities of legacy radar main powerhouse (magnetron, klystron and travelling wave tube) [1]. Using a large number of TRMs increases reliability compared to single point of failure of legacy radars.

D. Expected Performance

According to [41], based on LEO satellites operating in the L-band, the theoretical and experimental studies show that the power budget of bistatic radar for air target detection is sufficient for some practical applications such as detecting typical air-targets against a white-noise background at distances of 30 km and more. Such radar has unique advantages from the passive mode of operation, such as not being seen as an active surveillance radar and not having to power the transmitters.

There is the challenge of the direct satellite signal competing with the faint reflected signal from the target. This interference is many orders of magnitude stronger than the reflected signal. Another challenge is the high Doppler induced by the orbiting satellites illuminating the scene and frequent hand over from one satellite to the next in the correct position for an appropriate multistatic angle. This induced Doppler may compete with the clutter Doppler shift.

The favorable results reported [41] in the power budget evaluation are encouraging for further research into air-target detection with multistatic radar based on LEO satellite signals at higher frequencies as for the new constellations under deployment.

VII. Conclusion

CR is expected to provide improved situational awareness with more timely and precise information. It is expected to accelerate evolution of our D&S capabilities. This evolution could be managed by progressively introducing these capabilities as in service upgrades or integrated in the development of future systems. Replacing legacy radar systems as soon as possible with AESA TARs would enable updates to CR capabilities later when CR technologies are ready and mature. Upgrading to AESA TARs and then to AESA CRs would certainly provide progressively significant advantages to coalition forces in most demanding combat and surveillance situations.

It is worth noting that using AESA TRMs decreases the total operational energy demand and reduces nearby spectrum pollution from the non-linearities of legacy radar main powerhouse, i.e., magnetron, klystron and travelling wave tube.

Other cognitive sensors of interest to D&S were noted during this research. According to several references on SOund Navigation And Ranging (SONAR), cognitive technology and associated signal processing and pattern recognition have already proven to be advantageous in underwater operations. Similarly cognitive Light Detection And Ranging (LiDAR) provides accurate representations of the environment as applied to autonomous cars.

Another aspect is that the development of CRs may have stimulated work on CEW technology since most traditional electronic warfare techniques would not be able to effectively counter the nimble and unpredictable wave patterns of agile CRs.

Overall, there is overwhelming evidence that the advantages of adopting CR technologies outweigh the risk represented by their complexity.

As illustrated in Figure 2, one can infer that CR's shorter time to deliver higher accuracy track data increases the likelihood of target engagement success rate. This is a trend that several analysts would like to confirm with field trials in the near future.

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