The northern bat *Eptesicus Nilssonii*

SET-227 Task Group: Cognitive Radar

1. Introduction

Cognitive Radar is a topic that has attracted increasing attention over the past decade. The concept is intuitively appealing: a radar that 'thinks for itself' and in some sense 'learns' about the target scene and constantly optimises its operation in response to a dynamically-changing environment. The bat in the picture at the head of this article is a good example – this uses sophisticated echolocation (acoustic) signals to navigate and to detect and intercept its prey, and dynamically adapts these waveforms according to the changing target scene [1-3].

The ideas have their origins in knowledge-based radar processing and waveform diversity – both of which have benefitted from NATO task groups and Lecture Series. In particular, modern digital signal processing now allows us to generate precise, wide-bandwidth radar signals of any desired form, and to vary them from one pulse to the next. The ideas also have close similarity with Cognitive Radio, in which a radio transmission may be dynamically configured to fit into a dynamically-changing spectrum of other signals and interference. Indeed, an HF Over-The-Horizon Radar (OTHR) will employ an adaptive spectrum management system of just this kind.

The SET-227 Task Group has brought together some of the leading radar research groups in NATO nations to advance the understanding of the subject, and the purpose of this article is to describe the approach and the activities of the Task Group and to report on its findings.

2. The SET-227 Task Group

Despite the evident interest in the subject, at the outset of the study there was no clear agreement within the research community about a definition of cognitive radar. Also, virtually all of the work on the subject to date had been by means of simulations, and there was consequently a pressing need to perform some experiments to demonstrate that the ideas worked 'for real'. There was a perceived need to understand and quantify the potential benefits of cognitive radar processing, and also to understand any potential disadvantages. These requirements framed the objectives of the Task Group, which started its work in March 2015 with a projected end date of December 2017. Membership was drawn from 11 countries. During the course of the work some further members joined, and to give them adequate time to contribute the end date was extended to December 2018. The Task Group was co-chaired by Professor Hugh Griffiths (University College London, UK), Dr Alex Charlish (Fraunhofer FKIE, Germany) and Professor Nathan Goodman (University of Oklahoma, USA).

The work plan has been organised around seven themes:

- Context and definitions
- Cognitive processes
- Architecture and components
- Enabling technologies
- Methodology

- Techniques and approaches
- Challenges to the research community

each of which will form a chapter in the final report. The Task Group met twice a year, and maintained a sharepoint site so that documents and results could be shared.

3. Definitions and nomenclature

Adaptive radar processing has been around for many decades [4], for example, adapting the receive antenna pattern to suppress jamming by means of spatial nulls or adaptively setting a detection threshold to maintain a constant false alarm rate. Cognitive radar goes beyond that, to adapt the form of the transmitted signal in response to the sensing of the target scene.

Devising a satisfactory definition of cognitive radar has not proved easy. Although a significant number of papers and books have been published, there is no clear agreement on a definition of Cognitive Radar. Haykin [1,5,6,7] is keen to emphasize the Perception-Action Cycle (Figure 1) and that a cognitive radar possesses memory, which is updated by the information gained by the radar from the target scene. Another important criterion is stated to be that the radar should dynamically adapt its transmitted waveform in response to its perception of the target scene. Guerci's approach [8] owes much to earlier work on knowledge-based signal processing [9]. Yet another factor is that a cognitive radar should demonstrate 'learning', which implies that a cognitive system presented with a dynamically-changing target scene would be able to improve upon a previous encounter with the same target scene by virtue of the experience learned.

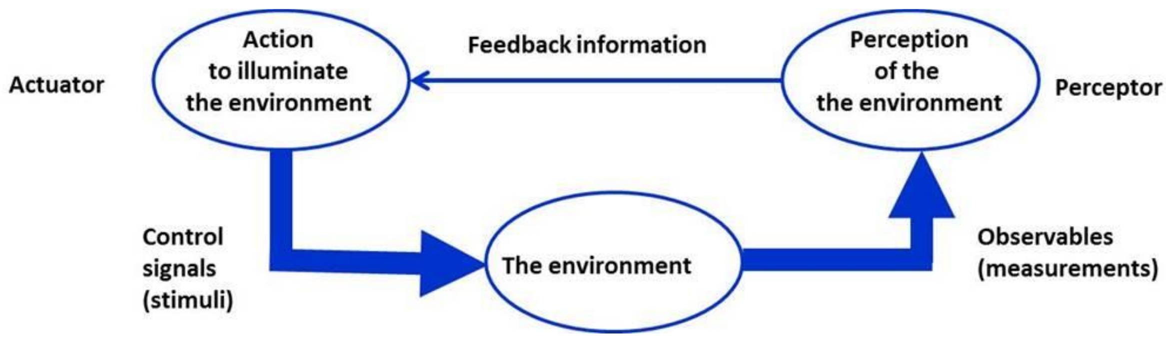

Figure 1: The perception–action cycle of cognitive radar (after Haykin [1]).

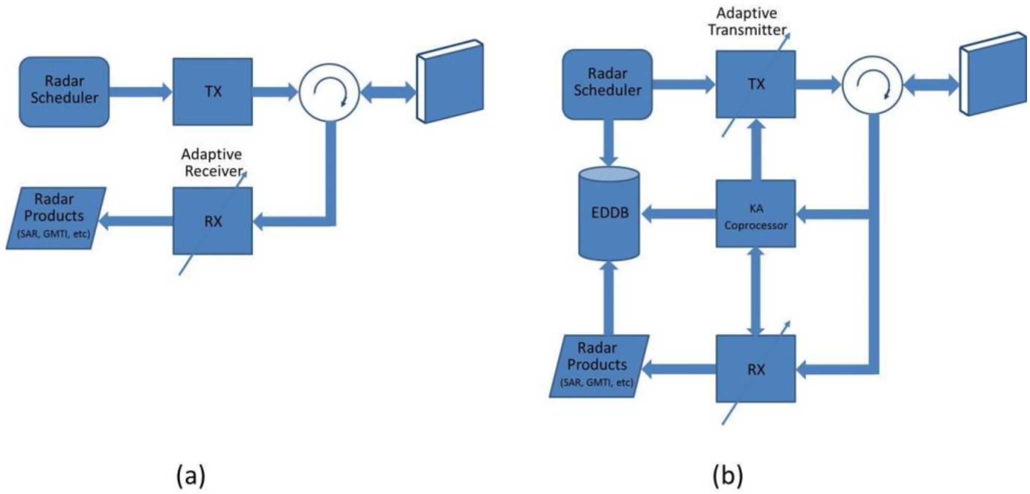

Figure 2: (a) Conventional Adaptive Radar; (b) Cognitive Radar (after Guerci [8]).

There have been various attempts to capture this thinking into concise definitions. Guerci [8] defines a cognitive radar as: 'A system that has all requisite knowledge and data to provide complete contextual machine awareness and all requisite adaptive transmit and receive DoFs [degrees of freedom] that are informed by such'.

Charlish has defined cognition as: 'The mental action or process of acquiring and exploiting knowledge and understanding through thought, experience and sensing', and has analysed cognitive processes in terms of *perception*, *memory*, *language*, and *thinking*, and stated the objective of a cognitive system as: *to transition cognitive processes performed by the operator into automated processes in the radar system.*

Some workers instead prefer the name 'Fully Adaptive Radar' (FAR), arguing that 'cognitive radar' may lead to unreasonable expectations of a radar that is so intelligent that it is way superior to any current system.

Horne et al. [10] suggest that, rather than seeking a single definition we should instead think in terms of levels of cognition, from manual feedback control at one end to full intelligent cognitive ability at the other.

At least for now, we advocate the IEEE P686 Standard Radar definitions (2018), which has: 'A radar system that in some sense displays intelligence, adapting its operation and its processing in response to a changing environment and target scene. In comparison to adaptive radar, cognitive radar *learns to adapt* operating parameters as well as processing parameters and may do so over extended time periods'.

4. Potential operational benefits

The Task Group has identified a number of scenarios in which cognitive behaviour may provide benefit.

Target tracking: In a multifunction radar environment the scene is likely to contain many hundreds of targets. The radar is required to track these targets, in addition to carrying out other activities such as volume search, and weapons control. Tracking high numbers of targets is expensive in terms of the available resources of radar time-line usage and computational loads. In principle the possibility exists to add more computer processing capability to the system, either by the addition of extra processing units, or by replacement with higher performing processors which naturally become available over time. However, the radar time-line cannot be upgraded, and instead we must find ways to use the available time in the most efficient way possible to fulfil the mission objectives.

Cognitive radar can relieve the tracking time issue in a number of ways. Trackers in multifunction radars schedule re-visit times in line with track state estimates and track quality requirements, such that track updates are generated in a timely manner to maintain track quality. Cognitive radar could enhance this process by reducing the re-visit frequency based on knowledge available to the system. Details of the environment in which the target is operating, and knowledge of the usual paths followed by targets through the locality, offer the opportunity for the radar to modify the re-visit interval due to the reduced uncertainty in its target and environment model. Further, the current signal to noise ratio of a given target, along with its predicted range at the next re-visit, allow the radar to modify parameters to reduce resource usage. Transmit power, pulse length, PRF and coherent processing intervals are examples of parameters which may be controlled.

The radar could also provide some degree of self-protection by employing LPI type signals in directions where hostile elements are identified. Such signals may not make the best use of radar resources, however, the sacrifice may be necessary. Additional benefits may also be available from the addition of a non-myopic view of the environment, whereby planning of future actions takes a longer term perspective, which avoids expensive re-acquisition of targets whose track loss could have been avoided given the appropriate actions [11].

Operating in spectrally congested environments: The future battlespace is predicted to be 'congested, cluttered, contested, connected and constrained' [12]. Dynamic environments which are spectrally congested present a challenge to any radar system. Cognitive radar can help alleviate the problem by monitoring the spectral nature of the operating environment, and modifying its own behaviour to exploit regions of the spectrum which are less populated, thereby optimising system performance. The system is required to monitor, and learn from, the operating environment, and from the derived perception, create suitable signals, which either avoids the congestion by operating in less congested RF regions, or manipulates the characteristics of its transmissions by introducing spectral notches around the interfering signals. Either solution offers the possibility of improved signal to interference plus noise ratio, compared with conventional operation, and provides for reduced interference to other users. The notched spectral content solution can provide wider bandwidths to the radar allowing higher range resolution to be achieved.

Target matched illumination: Improvements in signal to noise ratios may also be achieved by implementing target matched illumination [13] in the cognitive radar. The target range response is a dynamic process which is highly sensitive to the aspect from which the target is viewed. As such, in order to exploit this response and gain signal to noise ratio advantage, the radar will illuminate the target with some wideband signal in order to characterise the target over the band. The response is used in the cognitive processor to learn something of the nature of the target, allowing a waveform to be specifically designed to exploit the characteristics of the target. As the response may change significantly over small changes in viewing aspect, the wideband interrogation is repeated at intervals dictated by the cognitive processor's target model, which is learned over time.

There are also likely to be disadvantages and vulnerabilities associated with cognitive processing [14]. One may be that, if an adversary knows that a sensor uses cognitive processing, he may feed it stimuli that would in some sense cause it to ‘get into bad habits’. This remains to be explored.

5. Experimental work

Several of the organisations participating in the Task Group have conducted experiments to attempt to demonstrate and quantify the benefit of cognitive radar processing, and the Task Group has provided an opportunity to plan these experiments jointly and to compare results. It is realised that the experiments do not have to run in real time, and may, at least initially, be stepped through in slow time.

An example of an experimental system of this kind is the CREW (Cognitive Radar Engineering Workspace), conceived and developed by workers at the Ohio State University [15]. This is an indoor system, allowing experiments to be conducted under carefully controlled conditions. The use of W-band (92 – 96 GHz) provides for very high resolution in range and angle from quite small antennas. The peak transmit power is +25 dBm. Figure 3 shows one of the transmit/receiver heads.

Figure 3: Transmitter/receiver of the Cognitive Radar Engineering Workspace (CREW) at The Ohio State University.

The waveform is programmable by means of arbitrary waveform generators (AWGs), and the waveform and pulse repetition frequency (PRF) can be varied from pulse to pulse, or a library of waveforms can be preloaded and selected.

In one experiment, a human target walks around the target scene. The CREW radar dynamically adjusts the PRF so as to maximise the target signal-to-noise ratio, but at the same time ensuring that the sampling of the target Doppler shift is unambiguous (Figure 4). Although quite simple, this provides a clear example of the radar sensing the target scene and adapting the form of its signal in response. Further, more sophisticated experiments are in progress.

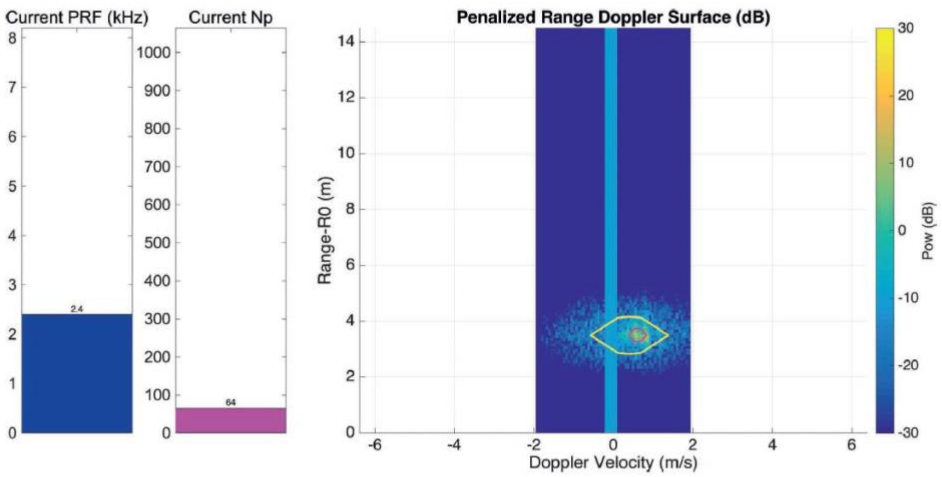

Figure 4: The two bars on the left show the PRF and number of pulses being integrated at any one processing interval. The right hand side shows a penalised range-Doppler surface where the target to be tracked will move in both dimensions [15].

6. Conclusions

Cognitive Radar represents an exciting set of ideas which may have profound impact on the form of future sensors systems. The ideas are not yet fully understood, but the SET-227 Task Group has made significant progress.

The work and results have been propagated widely by several means: a Special Issue of the *IET Radar, Sonar and Navigation* journal on Cognitive Radar [16] has just been published (December 2018). Special Sessions have been held at several radar conferences, including the 2015 IEEE Radar Conference in Washington DC and the 2016 Asilomar Conference.

Acknowledgement

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