USRP based cognitive radar testbed

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Abstract—**Cognitive radar is a relatively new field of research and the existence of low cost experimental testbeds is limited. This work will show the development of a low cost experimental testbed for experimental validation of cognitive radar algorithms. The testbed is based on USRP's, which is a low cost software defined radio developed by Ettus. Both the hardware and the software have been developed to provide a complete system for experimental validation of cognitive radar. Results will be presented that show the PRF of the test bed being adapted in response to the velocity of a non-cooperative target.**

I. INTRODUCTION

Cognitive Radar (CR) is based on the notion that the radar can form a perception of the environment by measuring it using electromagnetic energy, and using that perception can be used as the basis for decision making to support a goal or objective. The decision could be to use a different waveform or adapt in any of the degrees of freedom the radar has. Different strategies of this approach can be found in [1], [2].

CR adapts to the environment through feedback, normally from the receiver to the transmitter, and this allows the radar to operate more optimally in diverse and changing environments than non-adaptive radar. CR will have the ability to learn, such that when similar situations are encountered in the future, the optimal solution can be reached rapidly.

Using attention, the CR can focus it's resources towards the most important parts of the perception. It is common that a radar has finite resources available to it and multiple objectives to achieve, such as surveillance, tracking, weather monitoring, weapon guidance etc. Most commonly, the radar time line is regarded as the primary resource, however, other resources such as bandwidth, transmit power and processing power may also have to be manged. By focusing attention on critical parts of the radar's perception the limited resources can be shared between multiple functions.

CR has the potential of creating radars that uses resources more optimally, and that can be more adaptive to changing environments. This theoretical development requires experimental testbeds to validate results of CR. This work will show a CR experimental testbed using low cost software defined radios.

II. COGNITIVE RADAR RESEARCH

A CR uses ideas and principles derived in cognitive psychology that emulate how the brain works. CR is a relatively new field of radar research, sparked by the paper of Haykin [1] and book by Guerci [3]. Haykin's description of CR is built upon the thoughts of the neuropsychologist Fuster [4], who describes a mechanism he calls the perception-action cycle which is based upon the notion that the brain runs in a continuous cycle of selecting actions based on its perception of the environment. The actions will result in changes to the perception over time leading to selection of new actions, and hence the process is described as a cycle. The cycle is based upon reaching some goal or end-state, and actions are made such that the goal is reached in an as optimal fashion as possible, and with as low cost as possible. Haykin [5] describes the perception-action cycle in the brain as a feedback system between the perceptor, which can be seen as the receiver part of a radar system, and the actuator, which can be seen as the transmitter part. According to Haykin, memory, attention and intelligence are also required in CR.

Although Haykin's decription of CR is largely based on the work of Fuster and cognitive psychology, there has been a lot of work published on knowledge aided radar systems [3], [6] in a CR context. This work has been more focused on using knowledge together with adaptive radar and waveform diversity to optimize radar performance in applications such as Space Time Adaptive Processing (STAP). A large body of work in the waveform diversity and adaptive radar community [7], [8] has enabled the development of CR using many of the developed techniques for waveform selection and adaptation algorithms.

Research into biologically inspired methods is also considered to support the idea of a CR. [9], [10] show how methods most likely used by bats can be used for guidance and control of a robot in a maze. This research helps to demonstrate that a CR can be responsible for more than just adapting its waveform. The actions it selects can be steering commands for the platform that carries it. Under these situations, it is the change in platform position that results in the perception change required by the perception-action cycle.

Further work on CR is demonstrated in [11] where anticipation is used to find some optimal distribution of the tasks the radar must accomplish when there are known obstructions to these tasks, such as the need to dedicate a large amount of the radar time line to a specific objective like SAR imaging.

Bell et al. [12] showed a general CR framework, which can be instantiated for different tasks. Examples are given for a single target tracking problem, and for resource management of a network of sensors.

Sofware defined radios have been available for some years,

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and they have become very capable both in processing power and agility in waveforms they can transmit. Universal Software Radio Peripheral (USRP) is a software defined radio from the company Ettus, which has been an affordable and capable radio used in many research applications. USRP have been used in radio and radar applications [13]–[16]. However, despite the USRP's obvious flexibility a survey of radar literature did not yield any publications using USRP in CR applications.

III. SYSTEM REQUIREMENTS

For an experimental, active CR system, adaption of the receiver and transmitter is required to perform the perception-action cycle. Since the action could be adapted to a changing environment, the system is usually dependent on more than just selection between a set of possible waveforms. Computer processing power is also required to solve which action is best to achieve the goal, and this could take the form of both low level high speed processing power such as Field-Programmable Gate Array (FPGA) and higher level processors such as generalized CPUs.

IV. SYSTEM DESIGN

Certain software defined radio's have both flexibility in generating waveforms and control over the precise nature of the in the receiver chain. The National Instruments (NI) USRP-2952R [17] is a highly flexible software defined radio with a powerful FPGA. Combining this with a powerful host computer for high level processing would be sufficient to build an experimental CR system capable of achieving signal level adaption on the FPGA and more complicated radar function level adaption on the control PC. There has been some reported USRP based radars [13], [18], but to the author's knowledge none of these are suitable for use with CR algorithms.

A. Hardware development

The Software Defined Radar (SDR) system described here consists of several parts, but it's main component is the USRP-2952R [17] from NI. Fig. 1 shows a block diagram of the system, and images of the different components are given in Fig. 2. A list of components are given in Table I.

1) Software Defined Radio: The NI USRP-2952R, depicted in Fig. 2, is a device with high frequency agility and relatively large fractional bandwidth. The operating parameters are listed in [19].

The USRP is controlled from a computer through a PCI-express connection. While fast, this connection is still the limiting factor in terms of data transfer between low-level radar hardware and the processing computer. It is the inevitability of bottlenecks like this that are the driver for trying to separate the CR radar tasks into different levels.

1) HP Workstation laptop
2) National Instruments USRP-2952R 120MHz
3) PCI-express cable for connection
4) MiniCircuits ZVE-8G+ Amplifier
5) 2x S-Band horn antennas (30 degree beam width)
6) SMA cables
7) 12V DC Supply
8) Tripod and boom for antennas

Table I
LIST OF COMPONENTS FOR THE SDR

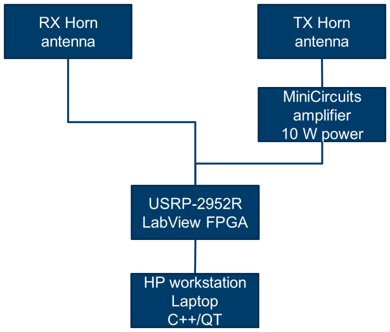

Figure 1. Block diagram of the cognitive radar system

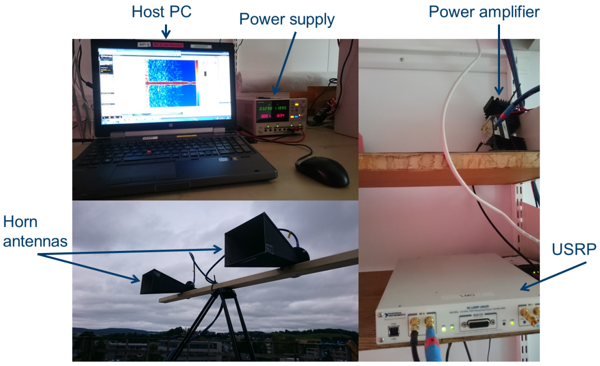

Figure 2. Pictures of the different components of the cognitive radar system

2) Microwave equipment: To achieve long detection ranges, a MiniCicuits ZVE-8G+ amplifier with an IP-3 of approximately 10 Watts is used to get a 20 dB amplification over the maximum output power of the SDR. As long as the waveform used is a rectangular single tone pulse, the output of the amplifier is only an amplified version of the waveform.

The antenna rig consists of two identical antennas, one receive antenna and one transmit antenna. The antennas were measured for beam pattern at an anechoic chamber, and the 3 dB beam pattern was measured at approximately ± 15 degrees around boresight.

The microwave equipment and the SDR are connected with SMA cables, and the antennas are mounted on a simple antenna rig built on a tripod and beam depicted in Fig. 2.

3) Simulation: A simulation was done in Matlab, using the hardware parameters found in this section. Standard waveform- and processing parameters were applied, to estimate the maximum detection ranges against targets of different Radar Cross Section (RCS). A threshold of 13 dB Signal to Noise Ratio (SNR) was used, to achieve 10^{-6} false alarm rate [20].

Fig. 3 shows the simulation of the SNR for a set of RCS versus range. The 13 dB threshold is also drawn to show the expected maximum detection range. The RCS of a small

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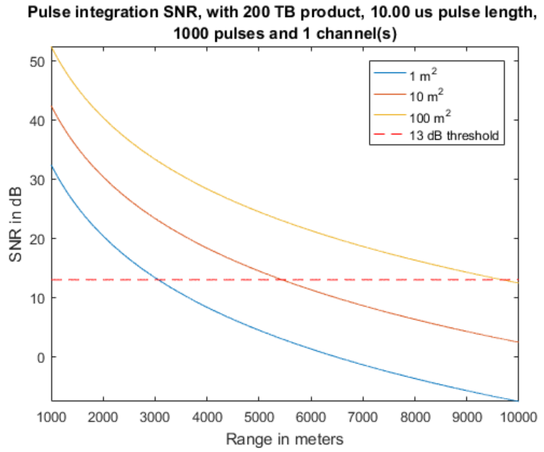

Figure 3. Simulation of radar system with a range of RCS

aircraft can be expected to be between 1 and 10 m^2 [20], and we can expect detection ranges of 3-5 km. For aircrafts with larger RCS, detection ranges of 5-10 km can be expected.

B. Software defined radar software

The programming of the SDR system has been done in C++ on a windows platform using the Microsoft Visual Studio C++-compiler (MSVC). It is built upon several external software packages which are given table II.

1) Radar processing: Transmitting and receiving data is implemented using the UHD library functions. A waveform vector is transmitted to the USRP, and the sampled data is transmitted back to the computer running the program. The waveform vector generation can be achieved on a Coherent Processing Interval (CPI) timescale, and is based on a range of parameters available for optimizing any wanted performance of the radar. Linear Frequency Modulation (LFM) with a flexible bandwidth and pulse length is currently implemented. However, so long as the amplitude envelope of the waveform properties are acceptable to the RF amplification stages any waveform may be used.

Processing of radar data is done in the program using the FFTW library for both fast convolution matched filtering and Doppler-processing [20]. A set of window functions can be used in both range and Doppler for side-lobe control. Detection is currently implemented by a set SNR-threshold and an algorithm to ensure that there is only one detection per target, since a single target can have many pixels above the threshold. Tracking is implemented as a linear Kalman filter for range-Doppler tracking. Parameters generated by a track are the prior and posterior state estimates and co-variance matrices.

UHD [21]	USRP Hardware Driver (UHD) library
Qt [22]	Qt is used for GUI programming
Qwt [23]	Plotting library for Qt
Boost [24]	Boost C++ libraries contains many functions
FFTW [25]	Fastest Fourier Transform in the West (FFTW) does FFT's

Table II
LIST OF DEPENDENT SOFTWARE LIBRARIES

2) Radar Graphical User Interface (GUI): A GUI is provided to control both the radar software and hardware, and display information relating to the processing, detection and tracking. Instantaneous and historical information regarding waveform parameters are displayed in plots on the sidebar, and track initiation is available in the GUI.

3) Waveform selection: To date, LFM only is used as waveform in the experimental radar system. The following parameters can be selected on a CPI-to-CPI basis; Pulse Repetition Frequency (PRF), pulse length, bandwidth, number of pulses, RF frequency and signal power. The implementation of Non-Linear Frequency Modulation (NLFM) allowing spectrum notching is planned as the next step, to enable the maximization of Signal to Interference plus Noise Ratio (SINR) on a pulse-to-pulse timescale [3]. Implementing the waveform generation on the FPGA in the USRP is key to enable spectral notching from pulse-to-pulse.

4) Cognitive algorithms: Currently, an algorithm selecting the PRF to achieve the best possible velocity resolution of a tracked target, while avoiding aliasing in velocity is implemented using heuristics. This algorithm is intended to demonstrate that the system can achieve the necessary parameter adaption required to test cognitive algorithms. Future implementation of NLFM with spectral notching to maximize the SINR is planned, where the different timescales on the PRF selection and the spectral notching would likely benefit from a hierarchical structure of the CR. Hierarchical structure is the main focus of future research for the author.

The perception-action cycle [1], [4] is based upon the availability of perception, which can be implemented in the Kalman filter, and action which can be implemented in the waveform selection process. Hence, it is possible to implement the perception-action cycle which, according to Haykin [1], [5], [26], is vital for a CR system. Memory and learning can be implemented using artificial neural networks [5], [27], and intelligence and attention manifests itself as algorithmic mechanisms [5].

V. EXPERIMENTAL VALIDATION

The radar has been tested on a range of target classes to analyze the detection performance and phase stability during Doppler processing.

Fig. 4 show the range-Doppler plot of a Boeing 737, detected at approximately 5.6 km range with SNR of 14 dB. The target was observed from behind, and likely exited the main beam shortly after this measurement was made. The detection range of large class targets was from simulations presented in IV-A3 expected to be between 5 and 10 km.

The CR can adapt waveform parameters from burst-to-burst, and currently adapts the PRF for a tracked target to provide optimal velocity resolution while avoiding aliasing in velocity. The zero Doppler notch is as narrow as possible and the risk of losing track during a zero Doppler crossing is therefore small. Fig. 5 depicts the tracker output for a car driving away

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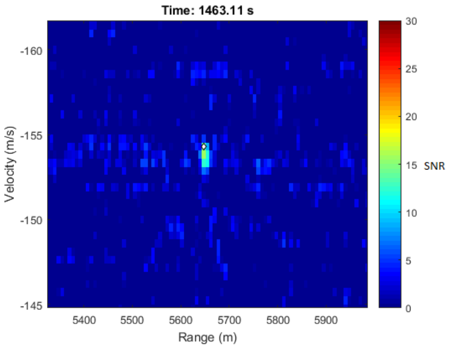

Figure 4. Boeing 737-300 detected at 5.6 km

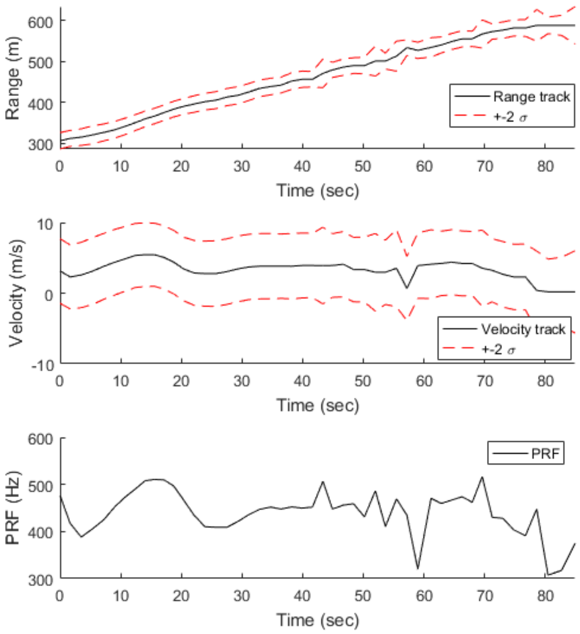

Figure 5. Adaptive PRF selection based on velocity track covariance

from the radar, where the top plot show range, center plot show velocity and the bottom plot show the selected PRF. The unambiguous velocity is proportional to the PRF which is adaptively selected based on the velocity covariance and speed of tracked target. When the target slows down, the PRF is small resulting in extension of the CPI to ensure a narrow zero Doppler ridge and a fine velocity resolution.

VI. CONCLUSIONS

This work shows a USRP based testbed for experimental validation of cognitive radar hypothesis. The experimental testbed has high adaptivity in selecting waveform parameters real time. The USRP has a large FPGA for high speed processing, and the system has a powerful computer for higher level processing. USRP is relatively low cost devices and this allows us to develop CR testbeds which is low cost and low weight.

Detection range of 5.6 km has been shown for a large airliner aircraft of type Boeing 737-300, and adaptive selection of PRF to maximize velocity resolution has been demonstrated.

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