# Cognitive Electronic Warfare: Conceptual Design and Architecture

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## Abstract

Computing revolution is heralding the transition from digital to cognitive that is the third significant era in the history of computer technology: the cognitive era. It is about the use of computers to mimic human thought processes, such as perception, memory, learning and decision-making in highly dynamic environments. In recent years, there is a growing research interest in the development of cognitive capabilities in radio frequency technologies. Using cognition-based techniques, a radar system would be able to perceive its operational environment, fine-tune and accordingly adjust its emission parameters, such as the pulse width, pulse repetition interval, and transmitter power, to perform its assigned task optimally. It is certain that traditional electronic warfare (EW) methods, which rely on pre-programmed attack strategies, will not be able to efficiently engage with such a radar threat. Therefore, the next generation of EW systems needs to be enhanced with cognitive abilities so that they can make autonomous decisions in response to changing situations, and cope with new, unknown radar signals. Because the system architecture is a blueprint, this paper presents a conceptual cognitive EW architecture that carries out both electronic support and electronic attack operations to synthesize close-to-optimal countermeasures subject to performance goals.

**Keywords:** Cognitive Electronic Warfare, Intelligent System Architecture, Previously Unknown Threat, Feedback-based Decision-making.

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## 1. INTRODUCTION

In recent years, there are more and more commentators who are talking about that we are entering a new third era of computing — cognitive era — making cognitive capabilities available on a large scale [1][2][3]. The two previous eras are: 1) the “tabulating era” (1900s-1940s) was made up of the early use of mechanical systems that can perform simple tasks as tabulate calculations; and 2) the programming era (1950s-present) is the era that began during World War II and today’s computing professionals have been so involved. It is marked with a shift from mechanical tabulators to electronic systems that can be reprogrammed to run different algorithms and carry out multiple tasks. The cognitive computing (2011-future) is the third era that brings with it a fundamental change with which cognitive systems are built to be able to think like human beings [1][4][5].

Cognitive computing takes computing concepts to a new level to mimic the way the human brain works [6], such as perceiving, thinking, learning, remembering and problem solving. Cognitive computing is a combination of cognitive science and computer science although they may have essentially differences from research objects and methods. Cognitive science refers to the interdisciplinary scientific study dealing with the process of cognition that investigates how information is stored, arranged and transferred in human mind. As an inter-disciplinary science, it encompasses the traditional disciplines of philosophy, psychology, computer science, artificial intelligence (AI), linguistics, neuroscience, and others [7]. Cognition originates from Latin [8], is a mental process of obtaining knowledge through thought, experience and the senses. It fundamentally controls our emotions, thoughts and behaviors. Human cognition is an adaptive complex system, which is changing, adapting and responding to the informational processing demands of interactive environments [9]. To catch the cognitive wave, there are growing research interests in the development of cognitive capabilities in various electronic systems in recent years. Mitola and Maguire first introduced the concept of cognitive radio in 1999 [10]. Haykin proposed the idea of cognitive radar (CR) that is a dynamic system to adapt and optimize transmitted waveforms based on the operational environment in 2006 [11]. As reported in [12], the development of cognitive electronic warfare (CEW) was recommended by a Defense Science Board study in 2013 to respond to adaptive radar systems and detect and counter tricky new sensors. Because CEW is a relatively new research area, there are not many articles on this subject. Most of the existing publications remain focused on introducing, explaining, and developing the concepts [13-16]. For example, in [13], the author discussed what is the cognitive technology, analyzed the differences between the CEW and adaptive electronic warfare (EW), presented the reasons why CEW is required to identify and counter future dynamic radar threats, and pointed out that “the true value and operational impact of cognitive EW will be seen in the battlespace”. There are a few other articles either focused on evaluating the performance of cognitive electronic support (CES) [17], or on cognitive electronic attack (CEA) [18]. In comparison, the major contribution of this paper lies in establishing a full system architecture with both CES and CEA sub-systems described in detail.

Since system architecture, which takes place within the design phase of the life cycle, is a blueprint that guides system development and defines the structural and behavior properties of the system [19], a high-level system architecture is presented in this paper as a starting point. Key architectural elements, such as components and system modules, are defined and the interactions among them are described. The rest of the paper is organized as follows. Section 2 introduces some background information on cognitive engineering and artificial cognitive system. Section 3 provides a brief review of CR. In Section 4, a CEW system architecture is established which decomposes the system into modules and defines the system’s behavior by specifying interfaces between units, as well as towards the environment. Finally, Section 5 concludes the paper with further scope of research.

## 2. COGNITIVE ENGINEERING AND COGNITIVE SYSTEM

As mentioned above, cognitive science is an interdisciplinary study of the mind, which is an umbrella term that covers a variety of approaches aiming to understand the mental phenomena of thinking, learning, decision-making, etc. It is not a unified field of study, but a collaborative effort among researchers working in various fields [20]. Norman introduced the term “cognitive engineering” in 1980 and suggested to develop this capability as an application-oriented partner to cognitive science [21]. Therefore, cognitive engineering is an application-oriented partner of the cognitive science, which focuses on applying findings about the fundamental nature of cognition whether carried out by human, machine, or a combination of them. As stated in [22], cognitive engineering is the application of knowledge and techniques of cognitive psychology and related disciplines to the principle-driven design of human–machine systems. It is about the design and development of computer-based systems that are analogous to that way humans acquire, store, retrieve, and process information. That is cognitive engineering combines cognitive psychology and information technology to design systems compatible with the way humans structure and solve problems, such as establishing a goal, executing the action, and evaluating the results. According to Norman [23], when people do things in our everyday life there occur 7 stages of action: 1) establishing a goal, 2) forming the intention, 3) specifying an action, 4) executing the action, 5) perceiving the system state, 6) interpreting the state, and 7) evaluating the outcome with respect to the goal (Figure 1).

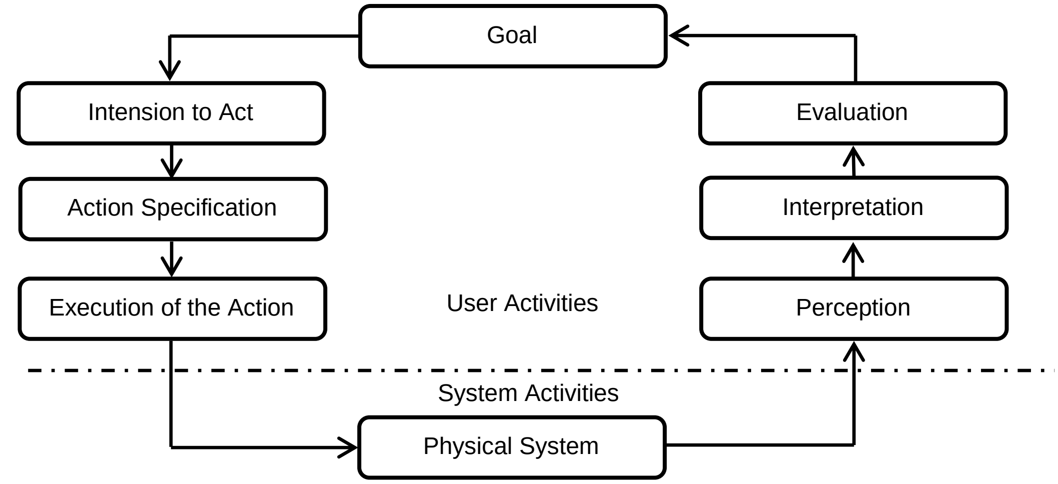


**FIGURE 1:** Norman's Seven-stages of Action Model.

Computer science has a very important role in cognitive engineering not only because computers can be used as tools to create, run, and test models of mental organization and functioning, but also can offer the information processing concepts and algorithms to perform tasks commonly associated with human intelligence [24]. Recently, the development of cognitive systems, oriented at modelling human abilities and performance, has received great attention [25]. A simplified model of human information processing, as shown in Figure 2, is the theoretical basis for understanding how cognitive processes are implemented for constructing the knowledge structures of computer agents in the system [26].

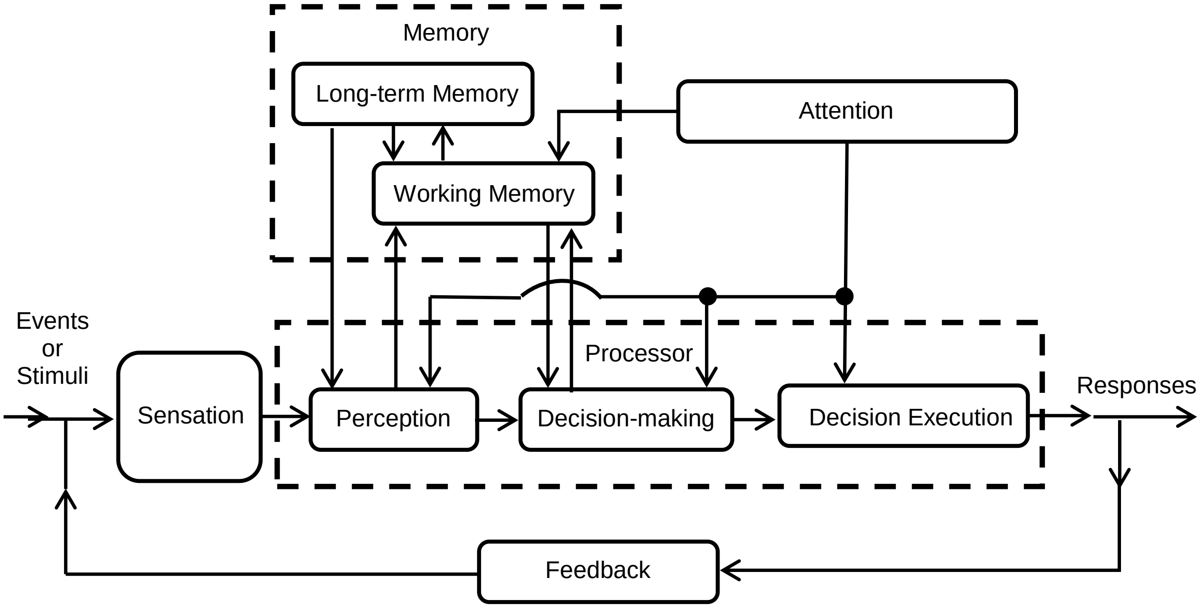


**FIGURE 2:** Wickens' Model of Human Information Processing.

The computer scientists and psychologists coined the new field of AI in 1956 with the ultimate aim of building computers and robots that could perform tasks commonly associated with human intelligence [27]. As stated in [28], "An artificial cognitive system is a system that is able to perceive its surrounding environment with multiple sensors, merge this information, reason about it, learn from it and interact with the outside world". It is not meant to replace human thought or actions — but rather to provide computational representations of human cognitive processes, and help people interpret the collected data and offer them conclusions [29]. The aim is to build cognitive models that mimic human thought process on the basis of Fuster's principles of cognition, namely perception-action cycle (PAC), memory, attention, and intelligence [30]. PAC is the backbone for system implementation, which forms a closed-loop feedback system between the actuator (transmitter) and the perceptor (receiver). It works reciprocally with memory to play an important role for recalling past actions and their effectiveness, holding environment information and current scenario, and continually updating the knowledge to predict the consequences of actions taken [31][32]. Attention refers to the efficient use of resources when dealing with a task. It is algorithmic in nature, which processes the perceptor output to extract information and concentrate on relevant observations [33]. Intelligence is the most complex one because it is built on the former three functions. The functionalities of intelligence include assessing events and conditions, reasoning about likely outcomes, and selecting the optimal solution through algorithmic decision-making mechanism [34]. As shown in Figure 3, the process cycle can be constantly repeated as a loop between perception and action with the environment as the external part and the controller as the internal part.

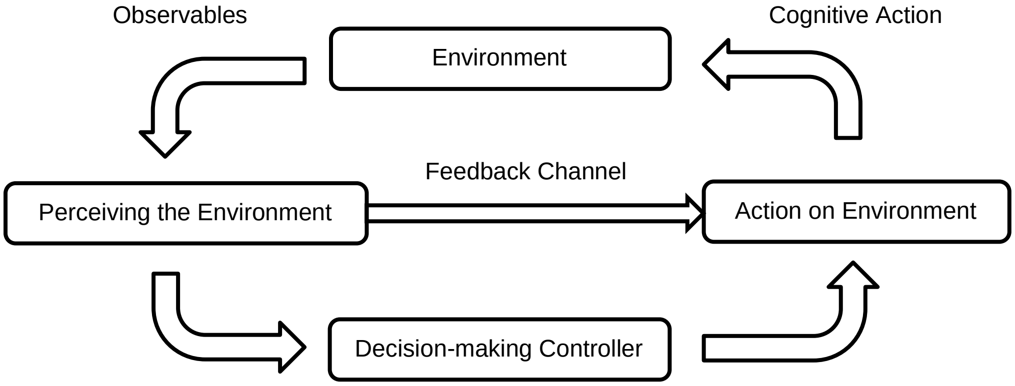


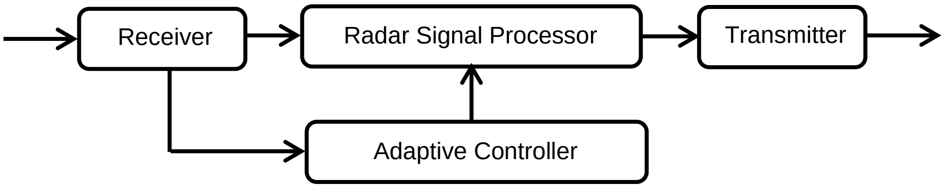
**FIGURE 3:** Perception-action Cycle.

As a summary, a cognitive system is an abstract framework that models brain perception. It perceives its surrounding environment via sensors to measure and estimate the environmental state. The decision-making controller plays a supervisory role that is responsible for perceiving the environment, conducting situation assessment, and determining the next actions taken to achieve the optimal control of the system. PAC is the circular flow of information in which any current perception can be stored to become the basis of memories that can be used intelligently to aid perception, apply attention, form predictions and engage actions [35]. Major characteristics of cognitive system include:

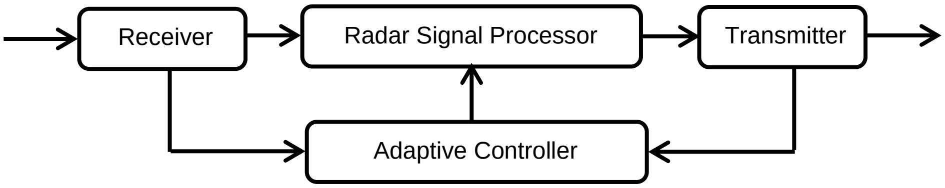
- Perceiving the environment in which it operates using whatever sensory input is available;
- Evaluating the acquired information and generating an environmental model;
- Processing information both acquired from the environment and recalled from memory to make judgments about the scenario;
- Learning and reasoning to select a specific action;
- Interacting with a changing environment to adjust controller parameters;
- Using cognitive feedback to create new perceptions, which then lead to new actions, and so on.

## 3. COGNITIVE RADAR

Since it was originally developed to detect distant objects in the 1930s, radar has been demonstrated as an effective tool for surveillance, tracking, and targeting applications in both civilian and military applications. With the widespread use of radio frequency (RF) devices, radar systems need to handle increasingly complex signal waveforms in dense signal environments — both self-generated and interferences caused by communication and other RF systems. The system performance in terms of detection, tracking, and target recognition in complex environments has become a serious challenge for modern radars. In the last decade, the radar world has been revolutionized by incorporating the adaptive and cognitive approaches. The theory of adaptive radar was introduced by Brennan and Reed in 1973, which aims to continuously maximize the probability of radar detection [36]. It is desirable to have an ability to adapt radar transmit waveform in adverse and crowded signal environments to optimally suit the needs for a particular radar tasking [37]. The adaptive radar systems can be categorized into two basic types: open-loop systems and closed-loop systems (Figure 4). Open-loop adaptive radar focuses more on the adaptation at the receiver to automatically adapt signal processing parameters [38]. Adaptive controller deals with the waveform design, such as coding, modulation and filtering of radar signals for target tracking, as well as adaptive cancellation to cancel the clutter effect and interference. In a closed-loop adaptive radar system, adaptive controller obtains feedback from the transmitter so that the optimization criteria can be determined based on both receiving and emitting sides. That is the current radar waveform will be considered in the calculations for the next measurement.



(a) Open-loop adaptive system



(b) Closed-loop adaptive system

**FIGURE 4:** Block Diagram of Adaptive Radar Systems.

Motivated by the echo-location system of a bat to adjust the parameters of its transmitted sound, the concept of CR was proposed to improve the radar performance with cognitive mechanisms. Table 1 shows a mapping between biological cognitive properties and CRs [39].

| Cognitive Property | CR Equivalent |
|---|---|
| Perceiving | Sensing/Communicating |
| Learning, Understanding | Machine Learning |
| Thinking, Reasoning, Judging, Problem Solving | Expert Systems, Rule-based Reasoning, Adaptive Algorithms and Computation |
| Remembering, Recalling | Memory, Environmental Database |

**TABLE 1:** Biological Cognitive Properties vs. CR.

Since it was introduced by Haykin in 2006 [11], CR has received a wide range of attention. As mentioned above, cognitive systems operate on PAC and memories. Figure 5 shows a block diagram of CR with a closed-loop PAC and a single layer of memory. The PAC encompasses the propagation of feedback information about the environment from the receiver to the transmitter on a cyclic basis. The perceptual memory is a long-term memory that deals with the incoming sensor measurement of the target and environment to enable identification and recognition. The working memory has a short-term nature for temporary information storage of prediction and attention [40]. The executive memory resides in the transmitter part plays a key role to achieve specific goals while action is being determined. By establishing a feedback structure from the receiver to the transmitter, a CR system forms a dynamic closed loop including the transmitter, the receiver and the environment [41][42].

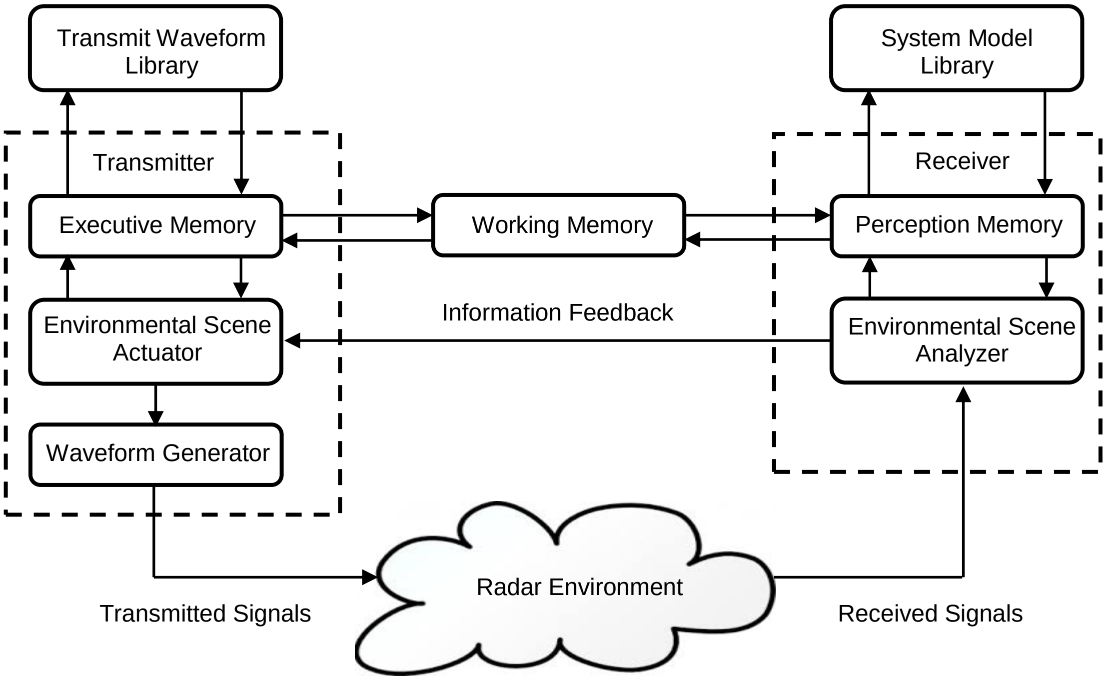


**FIGURE 5:** Block Diagram of CR with Memory.

The proposed CR system is characterized by the following four key features [43][44]:

1) The receiver learns, iteratively, from experience gained through interaction with the environment;
2) The transmitter adapts its parameters in an optimal manner in accordance with information about the environment passed on to it by the receiver;
3) The feedback link from receiver to transmitter makes it possible to optimize the operations of the transmitter by adjusting its illumination intelligently based on continuous learning the operational environment;
4) The memory plays a very important role in CR systems because a learning process relies on the ability to store and retrieve necessary information.

Unlike conventional radar systems that use the fixed transmit-waveform, cognitive abilities could allow radar to fine-tune and adjust its emission parameters, such as the waveform, pulse width, pulse repetition interval, and pulse compression technique, to perform its assigned task optimally. As an essential characteristic of CR system, PAC produces information about how the state of the environment is inferred by the system with the gain progressively increasing from one cycle to the next [42]. Further extending the concept of CR, the architectures of fully adaptive knowledge-aided (KA) radar [39] and cognitive fully adaptive radar (CoFAR) [45] were designed to improve performance and adapt to unknown environmental scenarios. The objective is to make the radar system be able to 1) effectively sense the environment; 2) learn from its experience; and 3) adapt to the changes. Figure 6 shows a conceptual framework of a cognitive fully adaptive radar that includes these three components.

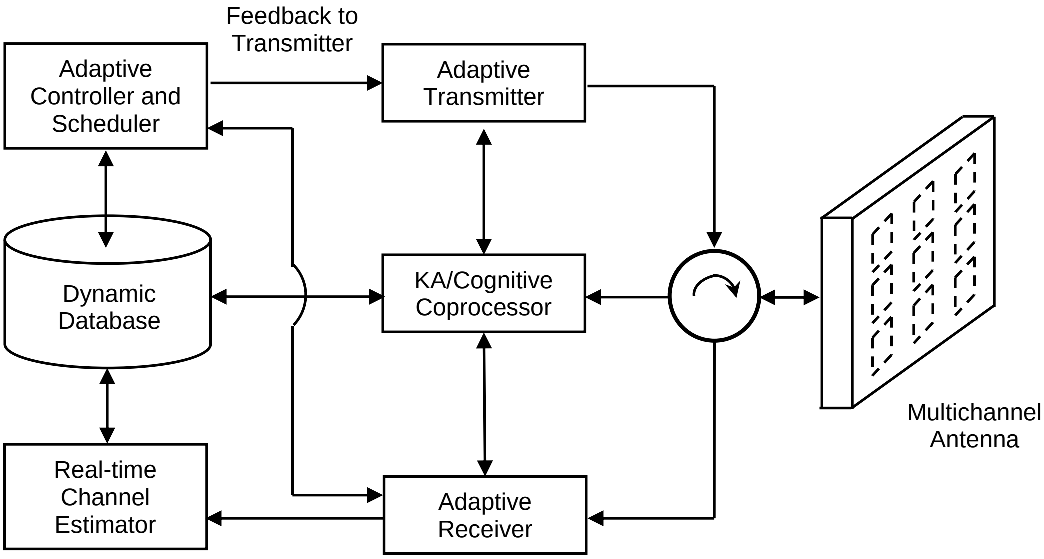


**FIGURE 6:** Illustration of Conceptual CR Architecture.

In Figure 6, the feedback from receiver to transmitter plays a crucial role to make the radar intelligently focus on primary targets but not be disturbed by the interferences or clutter. With knowledge of the transmit parameters, the adaptive receiver will thus perform corresponding pulse compression and optimize the receiver weighting vector. The KA/Cognitive coprocessor is introduced to guide the operation of transmitter and receiver functions in the processing back end. The system is operated based on a sense-learn-adapt framework with which observations, predictions, decisions and actions can be applied for adaptively detecting and tracking objects [46].

In summary, the concept of CR was proposed as an effective solution in increasingly crowded electromagnetic spectrum (EMS) environment within which the conventional radar has difficulty to obtain satisfactory performance. It is necessary to point out that there is often confusion over the terms of adaptive radar and CR that is called ‘advanced adaptive radar’ or ‘fully adaptive radar’ by some people in the radar community. As indicated in [47][48], a CR distinguishes itself from an adaptive radar in the following respects:

1) The CR embeds knowledge-aided processing and expert reasoning in both transmitter and receiver modes and adjusts its system parameters on-the-fly to match with highly dynamic working environments.
2) The CR is enabled to continuously learn from interactions of the receiver with the surrounding environment and update the receiver with the relevant information to maximize signal-to-noise ratio.
3) The CR intelligently and dynamically adjusts the radar illumination and transmission waveform based on the operational environment in an effective and robust manner.
4) The whole CR system constitutes a closed loop including the transmitter, the environment and the receiver called ‘global feedback’. It is the global feedback that makes the CR be able to refine the choices in uncertain varying environments.

## 4. COGNITIVE ELECTRONIC WARFARE

With the advances of radar technology, EW is also steadily improving as stated by Pettersson “Radar systems have traditionally been the main antagonist for EW systems in a continuous measures - countermeasures race” [49]. In the back-and-forth competition between radar and

EW, the winner is the one that can quickly incorporate the emerging technological advancements. Although fully CRs, inspired by the bat and dolphin bio-sonars, are not yet a reality [50], some attempts have been initiated to add cognition to conventional radar systems, such as adaptive waveform generation and optimization of target detection. Therefore, cognition is the key feature to defend against CR systems in the development of next-generation EW systems. A two-step deductive and inductive approach has been carried out. Based on principles of cognitive science, first a scoping study was conducted to build a conceptual framework of CEW system with a focus on the advantages of cognitive capability. Then, from reviewing the challenges of the current EW system against future CR, the CES and CEA sub-systems were developed with the relationships among each component as the procedures explained in [51].

### 4.1 Motivation and Drivers for Cognitive EW

Over the last century, EW has grown to become an important component of military operations since the implementation of radar system during World War II. It includes three major subdivisions: electronic support (ES), electronic attack (EA) and electronic protection (EP) for either offensive or defensive operations to prevent hostile use, but retain friendly use, of the EMS. An EW system consists of antenna(s), receiver(s), processing unit(s), and database to provide the means to intercept, identify, analyze and locate radiated electromagnetic energy, and then deploy countermeasures. Historically, EW systems were developed based on knowledge of specific, previously learned threats. The received RF signals are processed, analyzed, and categorized as either threatening or non-threatening associated with actions to be taken. The database contains two tables, one stores previous known threats that the system had been thoroughly tested against, while the other contains the corresponding pre-programmed countermeasure techniques. Thus, there exists a close cooperation between ES and EA divisions. Figure 7 shows a block diagram of conventional EW system.

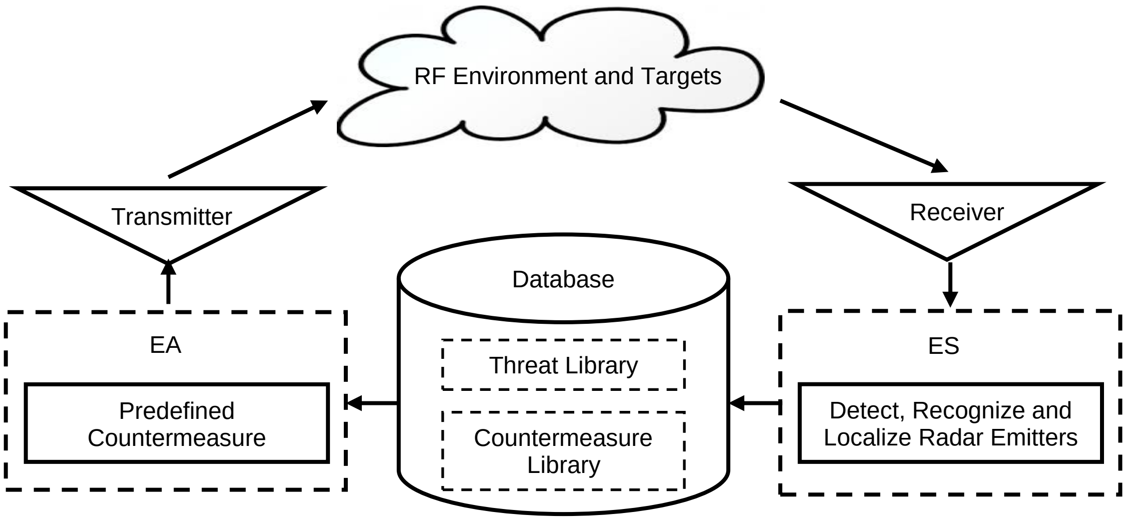


**FIGURE 7:** Block Diagram of Conventional EW System.

In order to detect, deceive, and defeat enemy radar threats, current EW systems must rely on known emitter databases to characterize the threat and deploy the response with pre-programmed countermeasure. When an unknown signal is received, the only thing that can be tried is to implement some generic countermeasures. However, this most likely cannot resolve the problem. In current operation, unknown received signal will be recorded and taken back to a laboratory for post-mission analysis and countermeasure development. As a consequence, conventional EW systems may lose the EMS dominance when encountering a new threat previously unknown to the system [52].

A hypothesis is that this challenge can be effectively addressed with cognitive technology by sensing, adapting and learning environment changes and possible interference, and embodying a feedback-based decision-making mechanism to intelligently deploy optimal countermeasures. Figure 8 shows a block diagram of generic CEW system. In the system, Environmental Perception focuses on sensing of the operational environment and observing the changes to optimize further processing procedures. Intelligent Signal Characterization uses machine learning algorithms to assess and characterize EMS signals and classifies them as either known or unknown threats. The objective of the CEA module is to synthesize close-to-optimal countermeasures subject to transceiver limitations, user-input restrictions and performance goals. Dynamic Knowledge Base contains not only a priori information of environmental and target aspects, but also information on recently learned threats. The feedback loop plays a key role in monitoring and evaluating the jamming performance, and adjusting the transmission parameters to achieve optimal effectiveness.

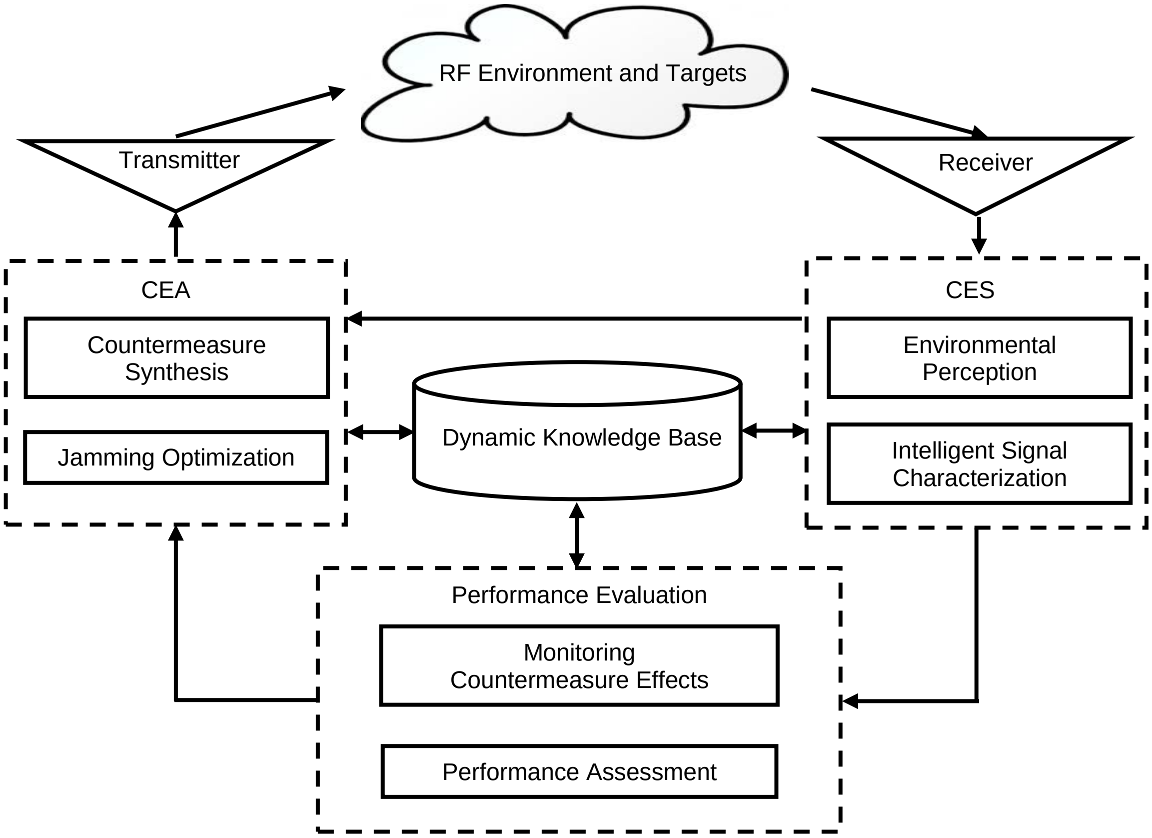


**FIGURE 8:** Block Diagram of CEW System.

In summary, a conventional EW system responds to a threat in a pre-programmed manner, either based on rules or pre-processed knowledge obtained off-line. A CEW system overcomes the limitations of the rule-based or knowledge-based EW system through continuous learning to make the system better aware of the environment in which it is being operated. The feedback loop not only connects the CES and CEA modules, but also includes the environment inside of the loop makes it possible to learn from interactions with the environment. It is the learning capability that makes CEW distinguished in comparing with conventional ones.

### 4.2 CEW System Architecture

In view of aforesaid, a CEW system needs to contain both ES and EA capabilities to detect, deceive, and defeat CR threats. Especially, the ES and EA modules need to be enhanced with cognitive algorithms and act together synchronously and coordinately. This collaboration ensures the system could identify source and intent of signals in a highly dense RF environment, and decide where and how to apply countermeasures to achieve optimum effects.

### 4.2.1 CES sub-system

As mentioned above, a CEW system consists of CES, CEA, performance evaluation, dynamic knowledge base, and feedback loop. Here, in the CES sub-system, the captured data need to be processed in two steps as shown in Figure 9.

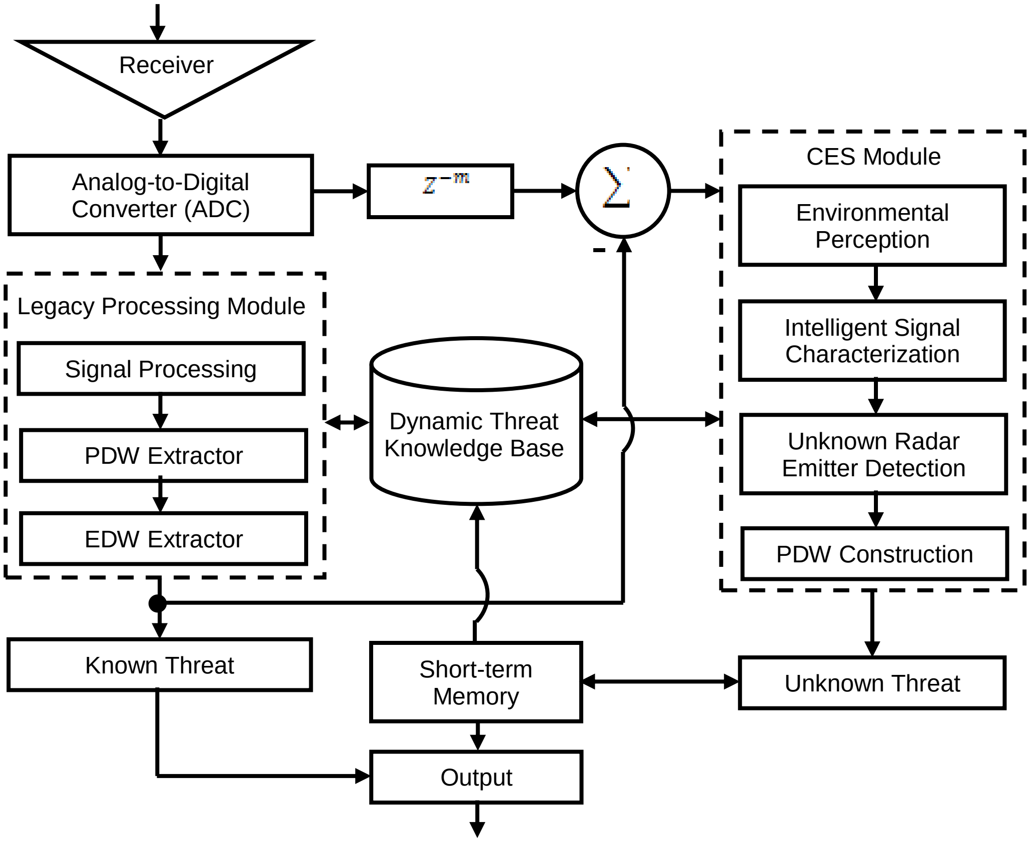


**FIGURE 9:** Functional Blocks of CES Sub-system.

First, the traditional ES method is used to identify and locate previously known radar emitters through the extraction and analysis of pulse descriptor words (PDW) and emitter descriptor word (EDW). Since PDW and EDW files are small, it is easy and fast to compare them against the database of known threats. Second, the leftover background data is fed into the CES sub-system to detect if there exist radar threats unknown previously. It is necessary to point out that an unknown radar threat can either be a totally new radar system that has never been seen before, or previously known radar system but with changed pulse parameters. It was indicated that to isolate unknown radar signals in dense electromagnetic environments and automatically generate effective countermeasures against new, unknown and adaptive radars, a combination of advanced signal processing, intelligent algorithms, and machine learning techniques needs to be developed [14][15][53]. In the CES part, the environmental perception module continuously learns about the surrounding RF environment through the database and the current measurements. Intelligent signal characterization builds on learning through interactions with the knowledge base to extract unknown signals by comparing the present and past accumulated knowledge of the operation environment. Different methods have been proposed to detect unknown radar emitters, such as support vector clustering [54], fuzzy clustering [55], and in-pulse characteristics analysis

[56]. Online learning is performed to create and retain new emitter threats in a short-term memory. These records make possible a later fine analysis to extract radar parameters for the intercepted unknown emitters. The initial estimations tend to be poor but will be rapidly improved as more data is collected. Finally, the resulting threats are updated into the knowledge base so that they can be retrieved in future ES efforts.

### 4.2.2 CEA sub-system

EA, another principal division of EW, was previously referred to as "electronic countermeasures" (ECM), which involves the use of directed energy, deception, and neutralization techniques against radars [57]. Radar jamming is the emission of RF signals to prevent or reduce effective use of a radar by flooding its receiver with noise or false information [58]. The objective of noise jamming is to mask the actual signal by injecting an interference signal into an opponent's radar receiver. Gaussian noise is the most common noise-jamming waveform that generally includes barrage jamming, spot jamming, and swept spot jamming [59]. On the other hand, deception jamming uses specialized waveforms to degrade radar performance. The objective is to mislead an opponent by manipulating its perceptions in order to degrade the accuracy of its intelligence and target acquisition [60]. Deception jamming can be performed with non-coherent signals and in that case the jammer is called a transponder, while repeater jamming generates coherent returns which attempt to imitate the amplitude, frequency, and temporal characteristics of the victim radar signal.

The concept of CEA was introduced in [13] for not only optimizing the jamming performance to counter those threats in the existing database, but also defeating previously unknown threats. As shown in Figure 10, there are two major countermeasure modules in the CEA sub-system to deal with previously known and unknown threats separately. The previously known threats will be responded based on the solutions stored in the countermeasure knowledge database with jamming scheduled to ensure friendly unimpeded access to the EMS.

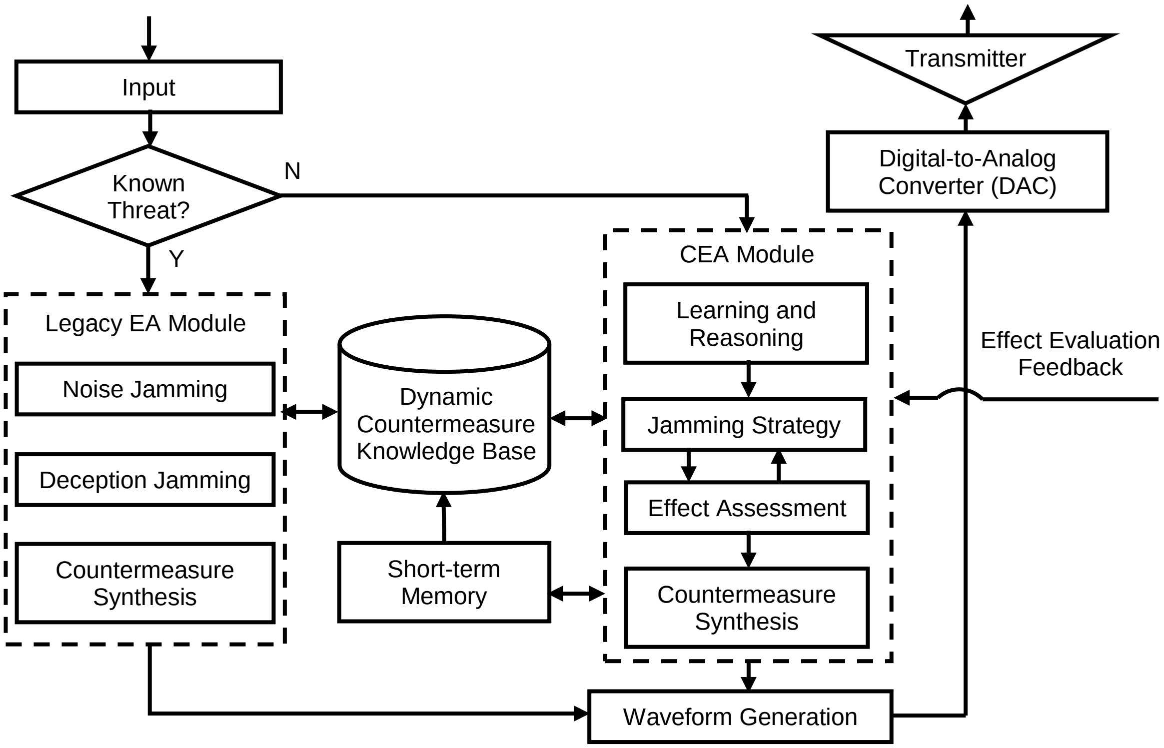


**FIGURE 10:** Functional Blocks of CEA Sub-system.

When encountering new emitter threats, it is not appropriate to choose an existing response in the countermeasure library, but to perform learning and reasoning to generate an action. Figure 11 shows a typical framing of a reinforcement learning (RL) scenario: an agent takes actions in an environment, which is interpreted into a reward and a representation of the state fed back into the agent.

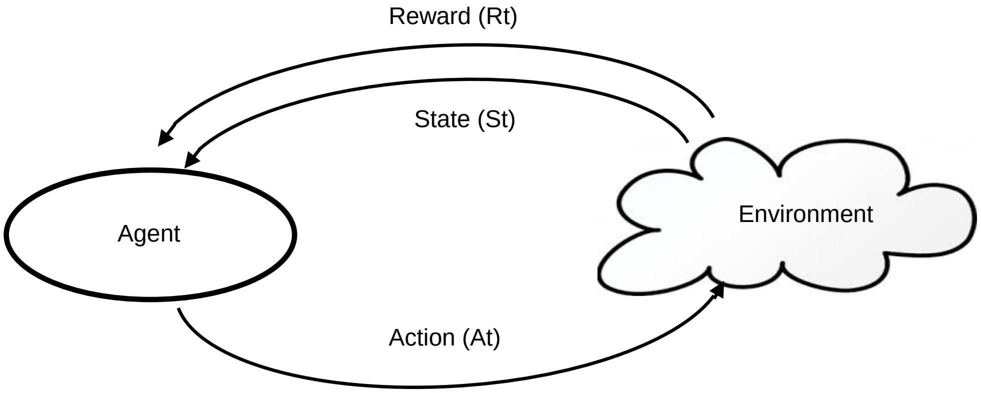


**FIGURE 11:** Reinforcement Learning Process.

Here, case-based reasoning, the way humans learn, is implemented which stores previous know threats and countermeasures and then proposes a jamming strategy when a new situation arises. A countermeasure is created and retained in a short-term memory, and improved based on the effect evaluation feedback which is obtained by identifying the differences before and after the jamming, such as frequency bands, radar functions and operation modes. Finally, the refined countermeasure is updated into the knowledge base so that it can be retrieved in future EA action.

### 4.3 CEW Summary

Based on above analysis, Figure 12 presents a conceptual CEW architecture with a key aspect of tight coupling between the ES and the EA. When dealing with a previously unknown threat, an action is constructed with respect to its interactional environment and the interactions of learning and reasoning instead of being explicitly pre-programmed. Online reasoning and learning are performed to create and retain new emitter threats in a short-term memory. A new threat label is created and corresponding jamming strategy will be sorted out based on the performance feedback. Once a satisfactory jamming effect is confirmed, the threat features and countermeasures are added to the knowledge base.

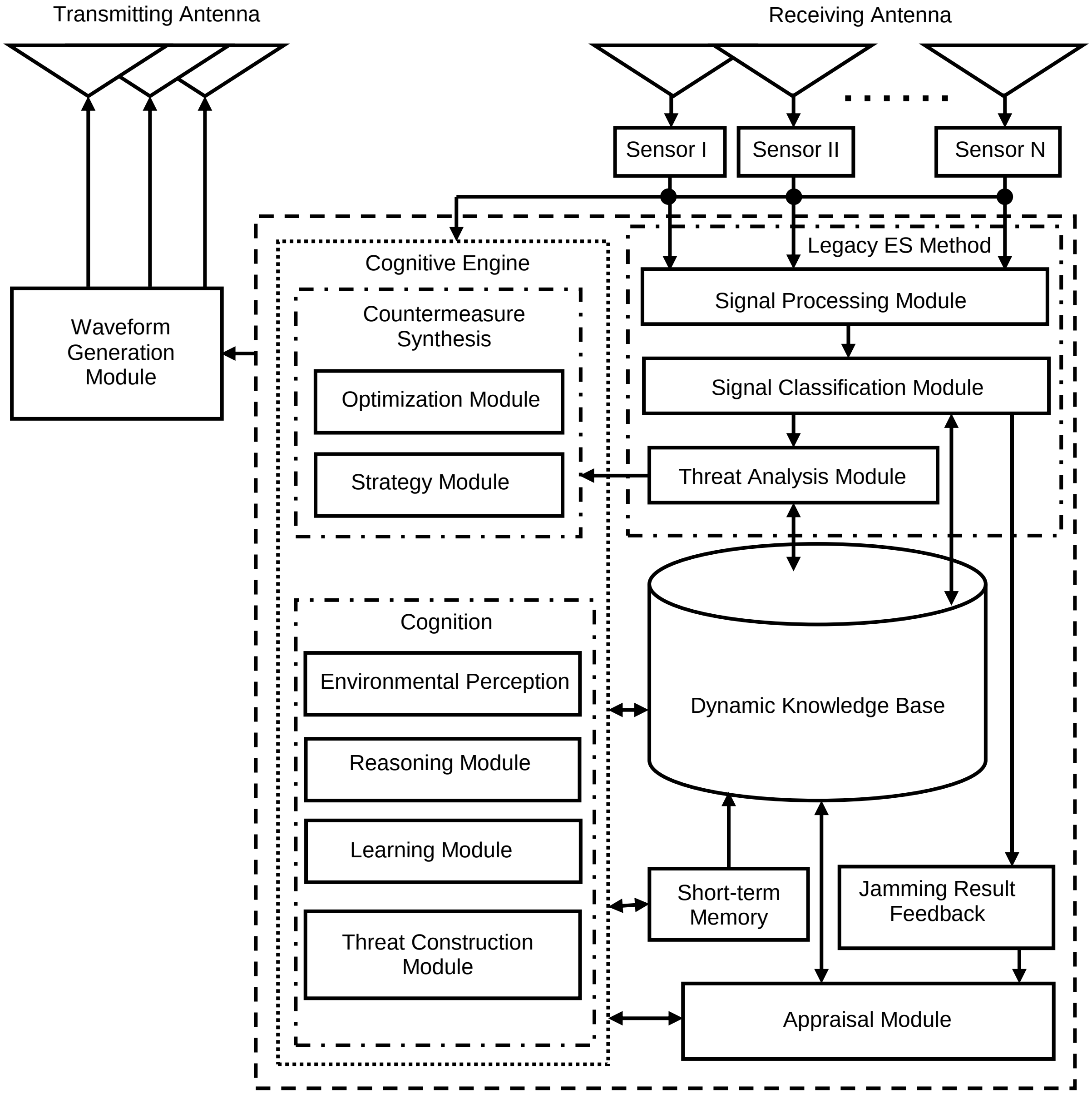


**FIGURE 12:** CEW System Architecture.

## 4.4 Case Study

A case study is presented to show the improvement and effectiveness of the proposed approach in terms of addressing the identified problem of coping with a new and previous unknown radar threat. As mentioned above, legacy EW systems rely on libraries of known emitter waveforms to detect, identify and defeat enemy radar threats. When new waveforms or previously unknown techniques appeared, the EW system needs to collect the signals in theater, take the data back and analyze it in the laboratory, and then spending some time to develop the corresponding countermeasures. Two major challenges with the legacy EW systems are as follows:

- When the received signal is slightly out of tolerance compared to what was recorded in the library, the threat emitter cannot be identified and defeated in theater;

- For the new and previously unknown signals, it may take months to develop new profiles and deploy countermeasures.

On the contrary, the proposed CEW system has the ability to detect, characterize, and counter both known and unknown threat transmissions in real time. In the CES sub-system (Figure 9), from signal processing point of view the previously unknown radar signal cannot be detected by the legacy processing module. After all the detected previous known radar signals are taken out from the data received, if there does not exist any other radar signal, the leftover data should be just random noise. Otherwise, if there exists a previously unknown radar threat, although mixed with the background data, its pulses will show some signal pattern. Therefore, it is reasonable to conclude that new or unknown radar emitters are present. The leftover data will be processed by the CES module to characterize the threat parameters that are then sent to the CEA sub-system. Based on the information passed by the CES sub-system, learning and reasoning are performed to generate a jamming strategy that will be modified if the feedback on jamming effectiveness is unsatisfactory (Figure 10). This case study demonstrates that by using cognitive methods the proposed CEW system makes it possible to detect, deceive and defeat previously unknown radar threats.

## 5. CONCLUSIONS AND FUTURE WORK

Radar and radar electronic warfare (REW), like a spear and a shield, were born almost at the same time and developed in the competition for spectrum superiority. With the evolution of radar technology from adaptive radar systems to cognitive ones, legacy EW systems have to be modernized to keep up with the fast-paced changes. The introduction of cognition into engineering systems has made it possible to construct systems that mimic human intelligence which is the key to the development of next-generation EW systems. By using machine learning techniques, it is possible to make the CEW system able to detect, deceive and defeat previously unknown radar threats. It is pointed out that a cognitive architecture is a blueprint for developing intelligent agents which specifies the underlying infrastructure of an intelligent system to model human behavior [61][62]. The intent of building a conceptual model is to direct attention at an appropriate decomposition of the system. Therefore, a conceptual architecture of cognitive EW system is presented in this paper, which integrates perception, learning and action components. The CES and CEA sub-systems and the relationships among each component are discussed in detail. The objectives are two-fold: (1) to functionally decompose the system into a meaningful integrated hierarchy in terms of its components and show the relationships among them, and (2) to identify directions for further research in the development of a prototype CEW system.

It was stated that the interest in CEW “reflects a recognition of the potential impact of applications of machine learning to enable more adaptive countermeasures to seize dominance in the electromagnetic spectrum” [63]. The intention of this paper is to provide theoretical background, general system architecture and key components for the development of a prototype system. Therefore, it is hoped that this paper can not only serve as a source of new ideas as well as a useful starting point for researchers and engineers who are interested in the field of REW, but also can benefit managers and policy makers in strategic planning for development of next-generation EW systems. As a scoping study, the research is conducted without the involvement of practitioners, which is a limitation of the current work. To achieve further progress, the vision of academics and practitioners should come together to jointly develop an action strategy in the next step [64]. Further research will be continued with focus on the following issues:

1) Develop analytic abilities to perceive the surrounding environment;
2) Implement fuzzy logic techniques to deal with environmental uncertainty;
3) Investigate the method to switch learning from batch mode to online learning mode;
4) Develop new algorithms that could detect and identify emitters with unknown behaviors and agile waveforms in heavily dense electromagnetic environment;
5) Design data management strategies for representing cognitive information in the dynamic knowledge base;

6) Develop new methods to perform jamming effectiveness assessment from the emitter side, but not the threat side, to optimize the countermeasure strategy.

The objective is to develop a proof-of-concept prototype CEW system with capability to adapt to existing radar threats and recognize new radar emitters in a complex, dynamic environment.

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