The Case for Cognition and Radar Sensing

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ABSTRACT

Cognition means 'knowing' and is the process by which we, as humans, come know about the world. However, in human beings this process is extremely complicated and although aspects of cognition are well understood there is far more to be learnt than is known. Nevertheless, humans and, of more relevance to radar, echo locating mammals, are able to sense their environment and interact with it in extremely sophisticated ways that are beyond the current capability of sensor systems. In this introductory module we examine the case for the role of cognition in radar systems. In part, this case is made by a desire to release potential latent in current radar systems. In addition, the case is also made through observation of the capabilities of natural examples of acoustic echolocation. The best known of these are: the bat, the whale and the dolphin but humans are also able to exploit echolocation. All demonstrate a remarkable ability to "see with sound". Using echolocation bats navigate, locate and capture prey. As a species, they have not only survived but have thrived in their environments, often solely reliant on echolocation. All echo locating mammals maintain a perception of their environment through the nervous system that allows them to take interact with that environment. All of these examples of natural echolocation systems are inherently cognitive.

Keywords: *Cognitive radar, Echolocation, Sonar, Optical Flow, Echoic Flow, Autonomous navigation, Target classification, Target recognition, Radar cognition, Cognitive sensing, Radar perception-action.*

INTRODUCTION

Radars sense their environment using electro-magnetic echolocation. The information acquired may be thought of as uneven shaped voxels of reflectivity in elevation angle, azimuth angle and radial range, usually updated on a regular or deterministic basis (PRF and scan to scan). This information might be plotted on a PPI display or as a high-resolution map like image in the case of SAR. Figure 1 shows an example of primary air traffic control radar. This rotates in the azimuth plane, detecting and mapping out the positions of aircraft in the sky. However, there also has to be some means of dynamically and repeatedly making decisions on the basis of the detected targets and their positions. In simple radar systems, such as air traffic control this decision-making is carried out by an operator who continually monitors the position of the aircraft to ensure that they take off and land in safety. It is this latter function that turns the radar sensor into a "cognitive sensing system", where the human operator supplies the cognition. Here, the term radar system must always embrace the operator when considering the full cognitive capability. I.e., it is the human who perceives the position of aircraft and provides the action in the forms of commands to the pilots, whilst the radar merely acts as the 'sensory receptor'. Of course it might even be possible to perform the function of the air traffic controller automatically given the relatively fixed procedural nature of the task. This, of course, would represent an autonomous cognitive radar system.

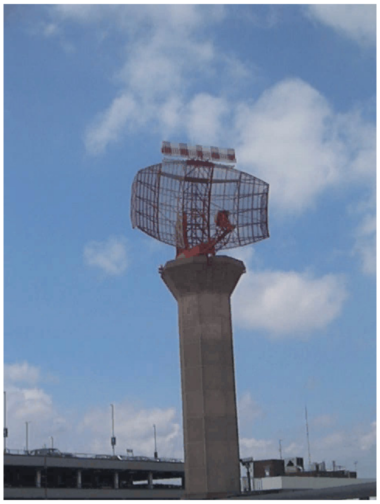

Figure 1: Primary air traffic control radar – Heathrow airport.

Now consider the case of an electronically scanned or E-scan array radar sensor. The advantages of electronic scanning are well known and can be crudely summarized as enabling the radar to position its beam anywhere at any time and with an ability to do this on a millisecond or pulse-by-pulse time scale. At a simple level this can be thought of as the radar sensor having the potential to modify its sensing parameters but on a timescale that is far too fast to be directed by a human operator. This immediately implies a need to synthesize, into the signal processing, aspects of the decision making normally carried out by a human such that it is the radar itself that provides much, if not all, of the control of the radar sensing parameters. Indeed, to achieve the full, latent, potential of an E-scan radar, a degree of cognition must be a part of the total system design. The role of the human may still be required but, perhaps, at a more editorial level, interpreting displayed information and passing instruction on timescales within the abilities of humans.

Ultimately, if truly cognitive processing systems emerge then potentially human operators could be removed altogether. However, the challenges of developing robust synthetic cognitive sensors to this degree of sophistication are immense.

The above two examples haven't yet explicitly considered other parameter variables such as power, beam width, PRF, pulse width, waveform modulation, polarization, etc. These can also be exploited together with the relative positions between the radar and the object or environment being sensed. A simple example is the detection of a target not in direct line of sight of the radar such as a target in the shadow cast by another object. A change in the sensor position can provide a direct line of sight and detection can again commence. This is a rarely used degree of freedom used by radar systems but is done instinctively in the natural world of echo locating mammals [1]. At a more sophisticated level the radar could automatically adjust its parameters to maintain a desired level of performance despite targets fades and changes in the background clutter. Dr. Smith will describe an experimental system that demonstrates these concepts in the last module of the lecture series.

Radar is also able to produce very high quality, very high-resolution imagery at prodigious rates. Figure 2 shows an example image of the Ohio State University Football stadium. The detail presented in the image is immense with many fine scale features being discernible. Such imagery can be produced in real time as an aircraft or spacecraft flies over a zone of interest. Indeed, space based systems can map much of the surface of the planet in just a few days. However, if a human interpreter or even a substantial number of interpreters cannot extract the valuable information contained in these images in a timely fashion, the effectiveness of the capability is drastically reduced. This means that automatic techniques are needed in order to extract desired information with high enough levels of reliability over very broad areas. Further, if this extraction can be done "on the fly", then areas of interest can be automatically re-imaged, providing extra information to corroborate findings. Again this leads to the sensor perceiving its environment and taking decisions as a result of that perception and again, at a high level, the benefits of a more cognitive approach start to become apparent.

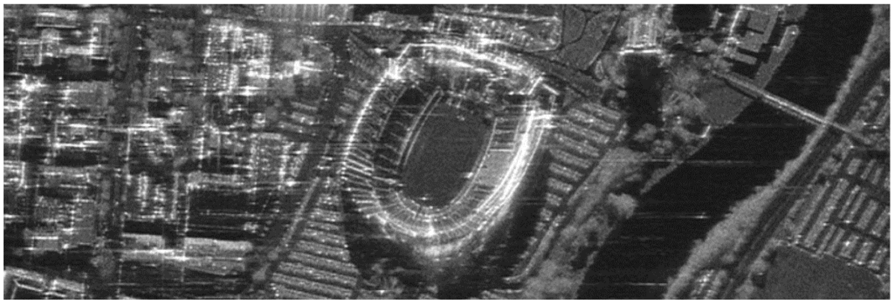

Figure 2: High resolution SAR image of the OSU football stadium.

There have been some early forays into these challenging but potentially extremely advantageous areas for future radar systems. There have been general descriptions such as [2], as well as more direct applications of cognition as in [3]. In addition there are related research examples of closely related research such as knowledge-based or knowledge assisted radar approaches [4].

Overall, radar and sonar systems have become indispensable tools for remote sensing, supporting numerous military and civil applications. Indeed, their utility has been greatly enhanced with the advent of electronic scanning arrays, high-resolution imaging, and space-time techniques for the detection of slow moving targets in dense clutter. New applications are constantly emerging, such as vehicular radar. Indeed, in the near future it is likely that all newly manufactured cars will carry multiple, highly capable radar systems. There is a huge on-going effort to uses such sensors as part of a system enabling driverless cars. This may well become an everyday example of cognitive sensing.

In recent years there has been emphasis on three main drivers that have fuelled much radar sensor development:

i) Increased signal to interference ratio
ii) Adaptive beam-forming and sidelobe reduction
iii) Improved spatial resolution

In different ways each of these has contributed to systems that have increasing sensitivity. As a result, modern radar systems, especially those that produce high-resolution imagery, receive echoes from all objects that are illuminated. As a direct consequence of this, much more emphasis has to be placed on being able to discriminate between different objects as opposed to merely declaring the presence or absence of a target. This trend of increasing radar sensitivity and improved spatial resolution is continuing.

High resolution, especially, lends itself to improved discrimination. Discrimination has the potential to radically transform radar and sonar from being a relatively simple observer of the world to being a sensor system that autonomously perceives and is therefore enabled to also decide and act. There has been much research devoted to discrimination and classification in the form of Automatic (or Aided) Target recognition (ATR). However, ATR remains a challenging and largely unsolved problem. Echo "signatures" are complex, exhibit much variability, and reliable interpretation of them has so far proven elusive.

For these reasons ATR remains largely the domain of the research community. Most approaches to radar target classification are linear, in that they sequentially process received echo data until some classification label can be assigned. The resulting performance is insufficiently reliable, even under ideal target observation conditions occurring within the context of laboratory or laboratory-like conditions (e.g. targets on a turntable or in an anechoic measurement chamber). Perhaps the best performing ATR systems are those that use 'signature information' such as jet engine modulation (JEM) templates or those able to provide a count of the helicopter rotor blades and their rotation rates [5].

More generally though, these linear approaches bear little resemblance to mammalian cognitive processes. Bats readily discriminate using echolocation to select sources of food. They appear to be constantly probing their surroundings with "calls", interpreting the reflected echoes (perception) to decide if a food source is present and then capturing and consuming the prey item (action). The process is adaptive and can be repeated with variation until a successful outcome is achieved.

Autonomous guidance and control via radar and sonar sensing is a highly sought-after capability with an enormous range of applications. For example, increasing traffic densities lead to an increasing and unacceptably high rate of road fatalities. It follows that technology able to prevent collisions, perhaps ultimately taking over the role of the driver, is of great interest. Radar has the potential to be a key component of such systems because of its proven ability to measure range and range rate in a simple inexpensive, discrete package regardless of time of day or prevailing weather. Processing echo information to enable autonomous collision avoidance is thus a very desirable objective and one that bats seem to have mastered.

COGNITION AND SENSING

The heart of cognition is the "*perception-action*" cycle that both creates and exploits memories [3]. Cognition may be autonomic or it may operate at a higher level and involve complex aspects such as "*thinking*". Cognition, as a topic of study in its own right, is extraordinarily involved and has been the subject of substantial research by many communities. For example, over the past 30 years there have been many laudable attempts to produce cognitive architectures within the artificial intelligence community [3]. These attempt to capture the essence of the cognitive process and are also based largely on a biomimetic approach. In the work presented here we draw heavily on the formulation presented by Haykin in [2] in which a memory driven perception-action cycle is first presented and applied to radar.

Cognition requires stimulation by sensors or by memories originally obtained from sensory inputs. In the human this is via hearing, touch, smell, vision and taste. The nervous system converts sensed stimuli into a "*perception*" of the world. This perception is sufficiently accurate for us to move around and to manipulate our world. In other words, we are able to take informed "*action*" by interpreting our sensory perception of the world and making behavioral decisions. Subsequently, the nervous system sends signals that activate our muscles thus enabling the desired action to take place.

The notion of perception and action may be embedded within a system. Consider, as an example, the reflex reactions of animals or a radar equivalent such as closed-loop tracking. These examples can be termed "*autonomic*", implying an automatic response rather than requiring contemplative thought. Conversely, perception and action can be external. Detecting an obstacle and deciding whether to walk around it to the left or right requires cognition at a higher level, necessitating informed decision-making (perhaps the route to the left is twice as long as the one to the right).

Closely coupled with perception are "*recognition*" and "*categorization*". Recognition and categorization operate on the output of a perceptual system and lead to the "*understanding*" of an environment or scene. Recognition and categorization are both informed by and assist in the creation of "*memories*". Memories might be derived from recent experiences, such as from a previous observation (e.g. a coherent processing interval in radar), or from earlier experiences derived from a similar situation. Both require effective creation and application of memories. Hence prior knowledge is an important resource and a key component of a cognitive sensing system.

"*Attention*" is closely related to perception and may be thought of as the requirement to allocate and direct the sensing resources towards relevant information. "*Decision-making*" implies the establishment of choices and the selection of one appropriate to a desired goal. In a radar system this process could entail, for example, changing sensor parameters to maintain a desired quality of track. The basis for determining the set of possible choices, resolving possible conflicts, and selecting the best choice varies in complexity depending on the task. In some cases this process may be enabled by the architecture whilst for others it is embedded within it.

Perception clearly plays a fundamental role in situational awareness and leads to "*prediction*". Perceptual information about entities and events combined from many sources takes the form of behavioral patterns that can be extracted and extrapolated into a prediction of the future. Prediction implies some form of a model of the environment and the effect actions may have on it (e.g. expected social norms). Such prediction enables generation of *"plans"* usually according to prescribed policies for carrying out tasks such as the order in which different targets might be interrogated or the deployment of resources in an electronically scanned radar system. Over longer timescales cognitive sensing performance will also benefit from concepts such as "*reasoning*", "*reflection*", and "*learning*" that facilitate adjustments to the underlying policies.

The application of cognitive-dynamic systems to radar and sonar sensing is in its infancy and whilst the above describes key components of a cognitive system it is beyond the scope of this module to address them all. Other modules in this lecture series will introduce some specific examples of cognitive concepts applied to radar sensing.

COGNITION AND RADAR SENSING

In the example of an air traffic control radar system, it was stated that the cognitive element was the radar operator. Indeed without the human interpreting the displayed aircraft information, communicating instructions to the pilots and observing the aircrafts being re-positioned, the system would exhibit no cognition and would be rather useless. Thus it can be concluded that cognition is not an option in a radar system but is, in fact, mandatory if radar is to realize its full potential. The issue is, how, and in particular how much, of the human operator function can be replaced by synthetic cognition built into the signal processing applied to receive echoes. Again, this is bought into sharp focus for electronically scanned radar systems where the radar is able to act and re-act on a faster timescale than is possible for a human being.

From the above we can usefully begin to divide radar cognition into two differing forms within the radar system. The first is in the setting and re-setting of radar parameters on a pulse-by-pulse basis with the aim of maximizing performance. This pre-supposes that the radar has been 'tasked' in some form. This tasking of the radar and the role this has in defining the required degree of cognition is critical. It is this tasking that provides the imperative against which the radar seeks to achieve success. In the final module of the lecture series we will see a working example where this has been implemented to perform tracking. Here, a cognitive approach allows the tracking performance to be pre-set to a desired level. The radar parameters are constantly adjusted to achieve the desired performance. Coming back to the air traffic control example, the operator has clear metrics in terms of safety distances, landing rates etc. These translate to a tasking environment that is relatively well controlled. Indeed, even in the case of unexpected and unusual behavior there is usually a script that is followed to assure safety. This is in stark contrast to, say, an air defence scenario where, implicitly, hostile air targets are attempting to avoid any adherence to a script and tasking is much less clear, dynamic and open ended. Nevertheless, in both situations the creation of the 'best' information is something that parametric adjustment can help with.

In addition, different tasks and the different type and distribution of targets will call for individually tailored radar parameters that aim to maximize performance based on an assessment of priorities. It is equally clear that the resources and resource timeline is finite and to optimize performance these resources have to be carefully utilized. Consider the example of the need for update rates on a receding target near to the limit of the detection range. It may be possible to use an update rate that is a lot lower than for a target at near range and coming straight towards you at high velocity!! A simple approach could be the use of multiple PRFs that vary, dependent on target range. In this way less radar resources could be used for the far target than the near target where they are most needed.

The self-setting of operating parameters in order to achieve a level of performance can be considered cognitive in a way that is consistent with a dictionary definition. However, if that were all, as in the case of an operator less air traffic control radar, the radar is still quite dumb. There is still a need for an operator whose role is to interpret the observed environment and make changes in some way in order to achieve a desired outcome. In the case of an air defense system under attack, this may be to launch a missile or deploy countermeasures. A successful missile launch would remove the hostile attack aircraft from the environment and the radar would redeploy its resources, again with the aim of achieving a desired picture of a complete air picture. This second, higher level, type of cognition that aims to bring about a desired effect is of a much more sophisticated and complex form of cognition and is one that can present a greater challenge to the radar designer.

Figure 3 attempts to illustrate the type of required architecture schematically and builds on the view of cognitive radar as a closed-loop dynamic system as expressed in [2]. In Figure 3, we separate out the sensor parametric adjustment from the broader action and decision space that creates the desired change in the observed environment. It is likely that much greater progress can be usefully made in the inner 'sensor' loop and the articulation of best picture by synthetic cognition. The outer 'action' loop presents a much more significant challenge but progress is being made in areas such as computer vision using optical imagery [e.g. 6].

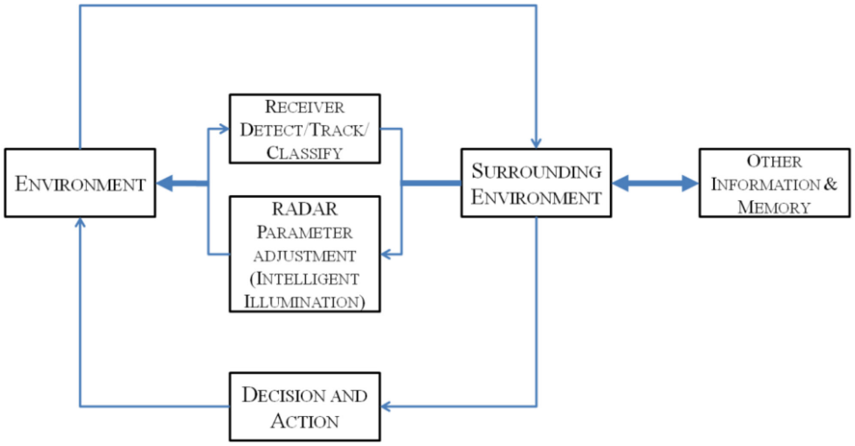

Figure 3: A simple schematic representation of a radar architecture that is cognitive enabled.

NATURAL COGNITION AND ECHOLOCATION

In this section we examine some specific examples of how cognition might be developed in a holistic manner taking cues from observations in the natural world.

Cognition in mammals typically involves the interplay between multiple sensory receptors and neuronal operations of immense interrelated complexity and magnitude. Indeed, it is likely that it is this complexity that allows such sophistication of actions and interactions. Bats provide an informative case study representing an extremely capable echoic cognitive-dynamic system. Specifically, they have been shown to navigate in a manner that is consistent with a description based on an echoic form of flow field theory. These “echoic flow fields” inherently embrace cognition through sensor “perceptions” linked directly to maneuver “actions”. Further, nectar-feeding bats are able to discriminate nectar rich flowers from a variety of alternatives. Feeding by the bat results in pollination of the flower, and hence reproduction of the plant species. Consequently, co-evolution has resulted in flowers that are easily identified because elements of their structure preferentially reflect the incident acoustic waves.

Together echoic flow and scene perception appear to play a key role in the autonomous ability of the bat to navigate and feed. Thus, an understanding of the sensing modalities and cognitive processing methodologies used by the bat could have immense and profound implications for future radar and sonar sensing leading to a plethora of new capabilities and applications.

Bats use echolocation for navigation, and nimbly avoid collisions with obstacles as well as with one another. They have evolved to feed at dusk and into the dark when many other animals, including some predators, are unable to fully function. All of this is achieved with a remarkable degree of agility and few if any collisions in highly-populated, intersecting “three-dimensional highways” [7]. It is echolocation that enables the bat to carry out these complex orientation tasks and to perform discrimination in complete darkness. The ability to navigate using radar or sonar seems tantalizingly close, especially as the technology exists that can match and even exceed the range of parameters used by bats. However, this requires the radar or sonar system to acquire a sufficient awareness of its surroundings (perception) for self-decision making, followed by application of motor forces to maneuver safely thorough those surroundings (action).

Cognition plays a direct and fundamental role in the abilities of bats. Radar and sonar systems also have to be able to “understand” their surroundings to a level that enables them to move about and interact with their sensed environments. This demands an ability to perceive, discriminate, make decisions and provide stimuli enabling action. Incorporating a cognitive approach into synthetic sensors systems has the potential to revolutionize their role in existing and new applications.

There are numerous examples of echolocation being used with great success in the natural world. Perhaps the most well-known examples are those of the bat, whale and dolphin. Here we limit ourselves to the bat that exhibits many characteristics that would be desirable to replicate in systems using radar. Bats have also had over 50 million years of evolution to hone themselves as holistic sensing systems of extraordinary ability.

Figures 4 and 5 show two calls in sequence made by a bat during the course of feeding from an insect. The insect was balanced on a pin and hence is not ‘on the wing’ but a remarkable number of observations can be made regarding the parameter selection during detection and attack of prey.

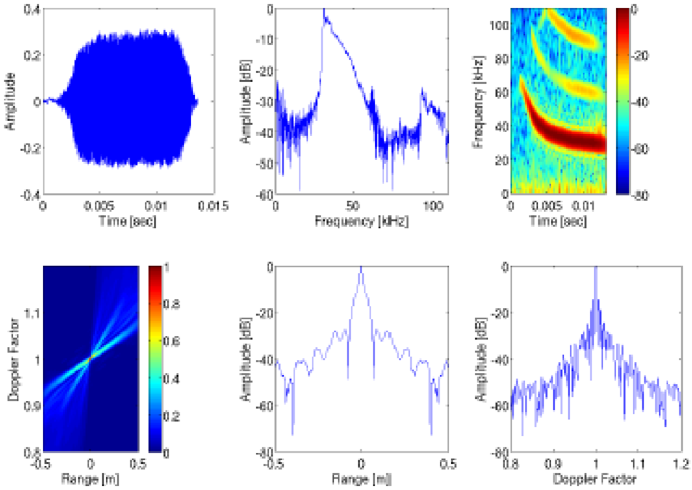

Figure 4: The Time domain, Power Spectrum, Spectrogram, and ambiguit function (with cuts through zero range and Doppler for a bat (Eptesicus nilsonii) call when appraoch an insect early in the engagement.

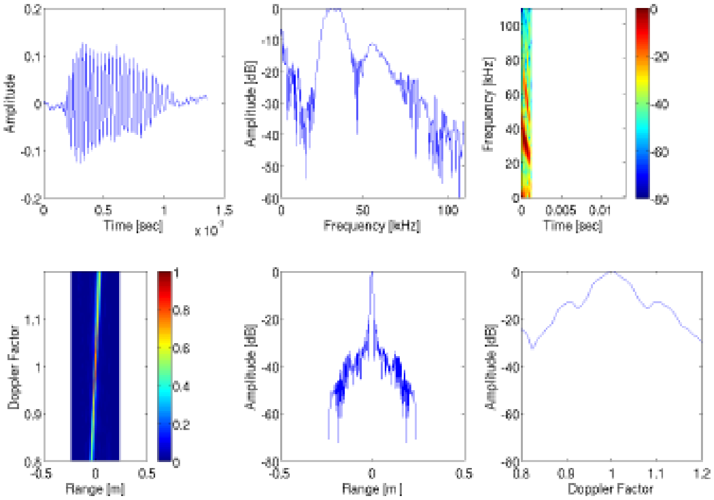

Figure 5: The Time domain, Power Spectrum, Spectrogram, and ambiguit function (with cuts through zero range and Doppler for a bat (Eptesicus nilsonii) call when appraoch an insect made at a later time than in Figure 3.

The spectrogram of the call (emitted pulse) made early in the engagement shows three harmonics each broadly with a longish constant frequency component but with a frequency modulation downswing in the early part of the pulse. The ambiguity function exhibits properties showing a resolution in both the range and Doppler domains. As the bat begins the process of intercepting the insect (on the top right you can see the entire sequence of pulses) a number of changes occur. Firstly, there are two distinct regimes of PRF. One is low, in the early phase and one is high, in the later phase. In this example the PRF is approximately constant but in others this is not the case. However, the flight time between pulses is normally long enough for the bat to ‘re-position’ it’s sensor via head and/or body turning and hence the sampling is far from uniform. Indeed the bat seems to be using information gleaned from predecessor pulses to take up a position of maximum advantage most likely a combination of detection, classification and location (but of course it's hard to ask a bat).

The "pulse" in Figure 5 is an example pulse from the final high PRF phase of the 'mission'. From the spectrogram it can be seen that the form of the modulation has changed considerably. The pulse length has shortened greatly (why transmit lots of energy when you don't need to) and the form of the frequency modulation is significantly different being close to hyperbolic with little or no constant component. This is mirrored by an alteration in the form of the ambiguity function whereby range resolution is high but there is little or no Doppler resolution. We might conclude therefore, that the bat has only need for ranging information (perhaps for aim point selection) and the momentum to intercept precludes the need for Doppler.

The examples of these two pulses show all sorts of parameter freedoms not normally utilized and exploited by radar systems. However, technology exists today to mimic such pulse and waveform agility. The question remains as to what the best parameter changes are? Of course part of the answer to this question sits between the two ears of the bats, i.e. in the cognitive processor!! Whilst neurological research has and is being conducted there is far more that is not understood about the working of the bats brain than is understood. The study of such high performance naturally occurring systems offers a rich environment from which many valuable lessons may be learnt and subsequently applied to take radar systems down a route towards the adoption of truly cognitive sensor systems.

BIOMIMETIC GUIDANCE AND CONTROL – ECHOIC FLOW FIELDS

Bats are able to perceive their environment such that they can navigate, avoid collisions, select targets and make decisions critical to their survival. They do this by adapting to the characteristics of the environment and continuously changing their echolocation sensing parameters such as the form of the call (frequency and depth and rate of modulation), call duration, the rate at which calls are transmitted, call amplitude and the direction in which the call is transmitted [e.g. 1]. This section introduces methods and strategies for collision-free guidance and orientation based on exploiting echoic flow fields and more details are provided in the last module of this lecture series.

Flow fields were first conceived by Gibson [8] and subsequently developed by Lee and co-workers [e.g. 9]. Flow field theory seeks to explain how humans and other members of the animal kingdom are able to navigate complex environments without having to compute and re-compute the position of all objects and obstacles along with the position of self. Flow fields naturally occur in many domains but most research attention has been on vision in the form of optical flow, see [9] and references therein. Optical flow represents the relative movement between a point of observation and objects in an illuminated environment as the ratio of light intensity to changes in light intensity. A human walking towards a doorway will exploit observed changes in the global pattern of scattered light. The instantaneous time to reach the doorway is automatically sensed and the nervous system controls the approach to, and transit through, the doorway.

Flow fields are a direct measure of the time for objects in relative motion to come together or, more generally, for a gap to be closed. The closure of a gap includes, for example, the closure of the angle between a current or reference direction of travel and a desired direction of travel. Distance and angle gaps can be combined enabling the computation of three-dimension flow fields. The derivative of a flow field determines how the gap will be closed. Holding the derivative at a constant value fixes the form of the resulting trajectory. A range of trajectory types can be chosen by selecting the value of the constant thus enabling different types of task to be carried out. Crucially, the sensed flow field (perception) can be used to directly compute the desired trajectory (action) consistent with [9]. In the case of humans a neuronal response stimulates muscles in the required way. Therefore measurement of gap closure times in both distance and angle (azimuth and elevation) provides a powerful basis for enabling autonomous behaviors in synthetic systems. The flow field or gap closure time is usually denoted with the parameter τ and this convention will be adopted here.

Bats have been shown [10] to perform tasks such as intercepting prey on the wing or maneuvering to a landing site in a manner that is consistent with exploitation of flow fields. Lee uses the term acoustic flow whereas here the term Echoic Flow (EF) is employed to specifically denote an active sensing system where acoustic or electro-magnetic signals are transmitted and received. In [10] it is concluded that bats use EF as a method enabling controlled landings and feeding on the wing. The behavior of the bat was found to be consistent with computation of τ and its derivative in both range and angle. Bats employ a strategy whereby the values of the derivatives of range and angle τ take a specific value. Radar and sonar systems inherently measure distance and angle using echolocation and thus lend themselves well to the measurement of 3-D flow fields. The flow field, τ, associated with radial range is given by:

$$\tau_r = r/\dot{r} \tag{1}$$

where r is the range to a detected object and $\dot{r}$ is the change in range of the object between the current and previous measurements. Strictly τ_r, r and $\dot{r}$ are all functions of time, t, however, here the '(t)' has been omitted for clarity in the equations.

τ_r is a direct measure of the time to collision or time to close the range gap and has units of time. For example, if a radar sensor system is moving directly towards a stationary object with a velocity of 5 ms^{-1} and the object is located at a distance of 10 m, the gap closure time is 2 s. Radars naturally measure range as a function of time and hence computation of echoic flow fields is trivially simple. Flow fields can also be computed in angle to provide basic navigation and collision avoidance data in three-dimensional space that is used both automatically and autonomously. In this way there are an excellent example of how cognition can be introduced to radar in a relatively simple manner.

TARGET RECOGNITION

A key ingredient in scene perception and hence cognition is the recognition and discrimination of different objects. Whilst echoic flow offers a powerful method for guidance and path planning it is only one aspect of the bat's cognitive process; another equally significant cognitive ability is the bat's ability to distinguish legitimate sources of nourishment from other objects. In other words, the bat is able to recognise desirable objects from their acoustic signatures, a capability that is highly desirable in radar and sonar systems.

By visiting flowers for nectar, the bat is responsible for pollen transfer between different individual plants and hence plays a key role in plant pollination. This means, although the short-term interest of the bat is solely efficient feeding, it is in the long-term interest of both the bat and plant species for pollination to take place successfully. Because of this, it has been hypothesised that co-evolution of bat and plant may have contributed to forming the shape and structure of bat-pollinated flowers in order to ease classification by bats [11], not necessarily a luxury offered to radar. Thus the ingredients for successful classification are in-built and this makes an ideal study case for deducing techniques applicable to synthetic echoic sensing. Recognition of flowers by bats is a demanding task, but nectar-feeding bats succeed in foraging using echolocation alone [e.g. 11, 12].

As a result of co-evolution, plants will have developed to provide clues in the echo responses obtained by the bat. In particular, bats have to distinguish between good flowers, wilting flowers and buds as well as timing their feed for maximum effect (efficient eating and energy consumption). It would seem likely, therefore, that characteristics indicating the difference between these flower states are embedded in echoes of the bat's cry to facilitate discrimination. In this research the floral echoes are examined to evaluate their dominant features and better understand how the bat might utilize them. Ultimately, this knowledge may provide information on how to interpret the target information available in manmade synthetic aperture radar and sonar images.

The "*Rhytidophyllum auriculatum hook"* is a bat-pollinated plant that grows in the Caribbean region and produces small flowers whose nectar is extremely attractive to bats (Figure 6).

Figure 6: The "Rhytidophyllum auriculatum hook" is a bat-pollinated plant that grows in the Caribbean region. The photo on the right shows a flower corolla taken from the plant grown at University of Bristol with its main components. The flower corolla was around 1 cm long.

Echoes from this plant are ideal for investigating the information sensed by the bats, as well as the relationship between the echo and the maturity status of the *Rhytidophyllum auriculatum* plant. Two datasets containing High Range Resolution Profiles (HRRPs) of an open flower and a bud of *Rhytidophyllum auriculatum* are compared in Figure 7. Of course we cannot be certain the bat processes received echoes as HRRPs but biological analysis has proposed bats to be sensitive to target range and the range differences between parts of a target [10].

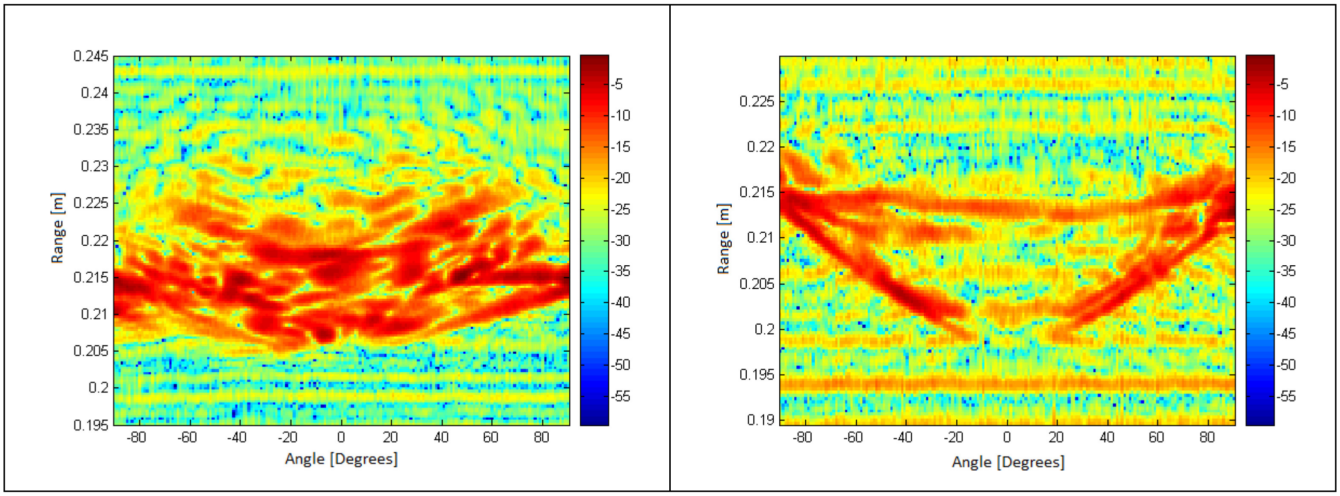

Figure 7: Magnitude of the HRRPs of a) a Rhytidophyllum auriculatum open flower and b) a Rhytidophyllum auriculatum bud. The structure of the bud is very different from that of the open flower. This may be thought as the flowers way to attract the bat attention. The color scale indicates the echo strength in [dB] normalised to the maximum echo value.

The bat has to be able to discriminate between nectar-bearing open flowers and closed buds. Although the form of the bat's neural signal processing is largely unknown, we expect the HRRPs of the bud to therefore be significantly different from those of open flowers. Closed buds are physically smaller than open flowers. Consequently the amount of energy they reflect is lower than for open flowers. Thus overall echo strength can be one factor in helping the bat distinguish between open flowers and closed buds.

CONCLUSIONS

Cognition in current radar sensors is, at best, at a very low level but is usually non-existent. A human being currently provides cognition in radar systems but is unable to react in timescales that radar operates on. In this module we have shown how radar systems can benefit from cognition and that to realize their full potential must include a cognitive approach. We have also drawn a distinction between low level, autonomic cognition and higher levels of cognition requiring processes more akin to thought in order to emphasize differing aspects of cognition as might be applied to future sensors systems. The dynamical parameter and 'platform' variation exploited by echo locating bats when transiting in known and unknown locales and when foraging and feeding offers an instructive example for mimicking and embedding more intelligent behavior into radar systems. Often this will include platform relocation as well as variations in waveform selection as a function of space and time. To develop truly cognitive radar systems there remains much to be done but to realize the true potential of technology advances such as electronic scanning there is little option but to pursue this route.

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