Discriminative Sensing Techniques

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ABSTRACT

The typical human vision system is able to discriminate between a million or so different colours, yet is able to do this with a chromatic sensor array that is fundamentally based on three different receptors, sensitive to light in the blue, green and red portions of the visible spectrum. Some biological organisms have extended capabilities, providing vision in the ultra-violet, whilst others, such as some species of mantis shrimp reportedly have sixteen different types of photo-receptors. In general the biological imaging sensor takes a minimalist approach to sensing its environment, whereas current optical engineering approaches follow a 'brute' force solution where the challenge of hyperspectral imaging is addressed by various schemes for spatial and spectral dispersion of radiation across existing detector arrays. This results in a problem for others to solve in the processing and communication of the generated hypercube of data. This paper explores the parallels between some of those biological systems and the various design concepts being developed for discriminative imaging, drawing on activity supported by the UK Electro-Magnetic Remote Sensing Defence Technology Centre (EMRS DTC).

1. Introduction

Defence operations are becoming increasingly reliant on the provision of persistent surveillance for a wide range of operational scenarios. Whilst advanced radar systems can address wide areas of interest at long range and track multiple moving targets, the resolution of those systems doesn't clearly identify those targets, yet alone provide sufficient information to inform the decision process required to determine whether objects in the field are threats or not. For that, it is necessary to turn to optical techniques, which provide the required degree of resolution. Recent advances in discriminative imaging provide a means of enhancing the accuracy of the identification process, so providing the military commander with additional knowledge relating to the intent of hostile force action. For unmanned air vehicles, the challenge of addressing diverse sets of targets with a reasonable level of confidence under all environmental conditions is setting goals for multiple sensor modalities. Solutions are especially attractive when several sensors can be exploited through a common aperture. At the other end of the scale, requirements for unmanned ground sensors, particularly for use in the urban theatre

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are also driving the consideration of concepts that provide different levels of functionality.

In the biological world, most organisms have an abundant and diverse assortment of peripheral sensors, both across and within sensory modalities. Multiple sensors offer many functional advantages in relation to the perception and response to environmental signals. This paper explores the parallels between some of those biological systems and the various design concepts being developed for discriminative imaging.

2. Bio-inspiration

Biological organisms have evolved to survive by exploiting multiple sensory systems. Diverse sets of sensors increase the probability of being able to discriminate stimuli. In insects, for example, some sensilla are innervated by both chemo- and mechano-receptors, enabling the spatial location of chemical stimuli. In many cases, the sensilla are modifications of hair structures, which have evolved over time to provide new sensory capabilities such as heat-sensing [1]. In the case of humans, we can sense light, heat, odours/taste, contact and sound. Our vision sensors are highly developed and provide us with the ability to discriminate and interact with our surroundings. The human vision system provides for highly precise spatial registration of all relevant objects in the external world. In comparison the fly has compound eyes, acoustic, heat and chemical sensors, organs to sense pressure, as well as the requisite neural processing cortex, all within an extremely small host organism. Its compound eyes provide the basis for sensing rapid movements across a wide field of view, and as such provide the basis of a very effective threat detection system.

When it comes to discrimination, vision systems have evolved to enable spectral, polarization and temporal signatures to be sensed. The cone structures in the human eye provide a colour discriminative function that is sensitive to over 1 million different hues, Yet it is able to realize this ability with what are basically tri-chromatic cone arrays. Here, a key characteristic is the degree of overlap between the spectral sensitivities of the different cone groups, which enables the eye/brain processing system to distinguish and recognize so many different hues. A very small fraction of female humans appear to have four different types of cone cells in their eyes and can distinguish as many as 10^8 different hues. The human visual system detects differences between the responses of the different groups of cones using sets of comparator cells in the retina and it is the outputs of those bipolar cells that provide colour information to the brain [2].

Whilst this is an impressive ability, a more complex vision architecture is found in the mantis shrimp [3]. Receptors in different regions of its eye are anatomically diverse and incorporate unusual structural features, not seen in other compound eyes. Structures are provided for analysis of the spectral and polarisation properties of light, and include more photoreceptor classes for analysis of ultraviolet light, color, and polarization than occur in any other known visual system; eight for light in the ‘visible’ portion of the spectrum, four for ultraviolet light, and four for analyzing polarized light. These photoreceptors are located in six parallel rows of specialized ommatidia running around the equator of each eye, each individually specialized for spectral and polarimetric analysis. Since the eyes are mounted on stalks and can move individually, they can address a wide field of view independently of the orientation of the shrimp. This implies that the visual cortex must be associated with some significant processing capability if the objective is to generate an image of its environment. On the other hand, by processing incoming information with a number of individually specialized sensors at source, the information leaving the retina can be streamed into a parallel series of data channels.

There are significant differences to be found between the ciliated photoreceptors as found in the human eye and the rhabdomeric structures found in arthropods. In the case of the mantis shrimp, the location of colour filters within the rhabdom enables an unambiguous identification of colour and by having sharply-tuned spectral responses reduces adaptation to out-of-band light. This enables the shrimp to exploit colour in their flamboyant signalling. It has been suggested that the overlapping fields of the two halves of each eye also provides a crude range-finding capability, which the shrimp requires to aim its uniquely-specialised claw for disabling prey. The fact that the action of the snapping claw results in cavitation-driven luminescence with a yield in excess of 10^4 photons per event is also intriguing [4], but the role of that light in signalling is open to conjecture.

Thus we can see that biological species provide a diversity of vision systems, underpinned by a well-developed ability to discriminate prey (or threats) in the natural environment. Whilst some of these architectures have already been exploited in engineered systems, others have yet to be realised, because of the underlying complexity of the biological design.

3. Discriminative Imaging Techniques

In the context of military surveillance systems, a discriminative imager is one that enables a target to be distinguished from its surroundings. To meet that objective, it is necessary to address particular attributes of the target and to counter any camouflage, concealment and deception measures that may be exploited by adversaries. In that sense, the position is very much the same as that faced by biological organisms in striving for survival in the presence of natural threats. Various approaches can be followed towards achieving useful levels of discrimination, including the exploitation of geometric, polarimetric, spectrometric or vibrometric characteristics of the targets.

3.1 Passive Discrimination

There has been a great deal of work done in exploiting hyperspectral and polarimetric techniques. In the former case, the emphasis has usually been in splitting the incoming radiation into discrete "bins" (generally using a prism or grating) and providing a means of processing the information associated with the ensuing 3-dimensional hypercube in an efficient way. This provides challenges in relation to the exploitation of such cameras in the context of network-centric warfare, since it places increased demand on communication bandwidth. The problem is particularly relevant in the case of persistent surveillance systems, which rely on timely communication of events to the field commander. Similar approaches have been taken in polarimetry, where the incoming optical field is usually analysed using polarising beam splitters and recorded using separate focal planes arrays for each plane of polarisation. The challenge then is in image registration and ensuring that the polarimetric signature displayed is characteristic of each point in the far field.

A different approach has been followed by Thales [5] in work supported by the EMRS DTC, exploiting the fact that QWIP detectors require the provision of gratings to ensure optimal coupling of incident light into the detector element. By providing differently oriented gratings on each 2x2 group of detector elements, and micro-scanning the incoming image field across the 2x2 group, it is possible to extract the polarimetric signature of each point in the far field. Characteristics of the geometry of objects are clearly revealed and can be used as an input to anomaly detectors and target recognition algorithms.

Relatively simple algorithms can be used to generate the polarimetric image. In the Thales approach, the scheme used is as follows:

$$I = 0.5*(I_0 + I_{45} + I_{90} + I_{135})$$
$$Q = I_0 - I_{90}$$
$$U = I_{45} - I_{135}$$
$$P = \sqrt{(Q^2 + U^2)}/I$$

Here the I_x terms denote intensities measured at the different grating orientations. It is significant that the processing of the image exploits differencing, similar to the way that the human eye processes information before it is passed to the cerebral cortex. However this places demands on the signal-to-noise ratio of the detection system, since each arithmetic operation degrades the quality of the image.

A similar form of process can be applied in principle to hyperspectral sensing. For many years, particularly in the area of colour science, hue has been represented in the visible band in terms of its CIE coordinates [6], defined in relation to the three colour-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$. There is a loose correspondence between these functions and the response characteristics of the cones in the human eye. The CIE coordinates X, Y and Z are then determined in relation to a set of integrals based on those colour-matching functions. The CIE XYZ colour space was deliberately designed so that the Y parameter forms a measure of brightness, whilst chromaticity is defined by two derived values x and y. Thus the spectral and intensity characteristics of visible light can be represented by the three constants x, y and Y. When pre-detector processing is applied through the provision of colour filters on the different elements of a detector array, the spectral forms of $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are defined by the filters themselves.

Just as in the case of the human eye, it should be possible to exploit IR detector elements that have essentially Gaussian spectral response functions, but with some degree of spectral overlap between the different elements in each discrete grouping. Once again, the QWIP detector provides an almost ideal response function, with full-width half-maximum (FWHM) values that can be engineered by design. Multi-color infrared focal plane arrays (FPAs) can also be realized by stacking different multiple quantum well layers capable of acquiring images in each relevant IR band. For example, the group at JPL [7] developed a dual band 6-10μm and 10-15μm array, which exploited different grating depths to couple the incident radiation into the different elements of the detector.

The group at Thales [8] is also exploiting QWIP detector technologies to demonstrate a 3-band LWIR imager, with a goal of providing a combined spectrometric and polarimetric imaging capability. Here three of the individual grating designs in each 2x2 element group on the QWIP detector array are adjusted to provide three different peak wavelengths at 8.2, 9.1 and 10.4μm. The fourth element also provides a response at 9.1μm but with polarization characteristics orthogonal to those of the first. By exploiting the same micro-scanning technique as used in the polarimetric version of the camera, it should be possible to generate enhanced levels of scene discrimination, sufficient to locate signatures of various minerals in soil.

Spectrally resolvable features useful in the defence context can also be found in the visible, especially near the chlorophyll absorption edge, and in the short-wave IR (SWIR) band, where there are features arising from overtones of the hydroxyl vibrational band in water near 1.14μm and 1.4μm. Due to the significant differences in water content between natural and man-made objects it is possible to exploit the hyperspectral datasets as inputs to anomaly detectors. In the SWIR band it is also possible to generate a false colour image of scenes using a colour-coding scheme intelligently chosen to emphasise the contrast between natural and man-made objects.

So, just as the human eye can distinguish many different hues, it should also be possible to train a processor to carry out the same task using a minimal training set. Pratt and Nothard [9] have developed a technique for detecting broad material classes in arbitrary imagery. The broad classes were terrain, healthy vegetation, other vegetation, background and blackbody. Careful selection of the classes and bands provided a robust sub-pixel detection method for airborne hyperspectral sensors. A simple method was also found of extracting the atmosphere from unknown pixels based on a correlation approach using the mean of the blackbody class.

Another approach towards extracting a meaningful hyperspectral response has recently been suggested in the work of Rogers and Bernhardt [10]. Their technique exploited the variation in spectral response within an imaging array to perform spectral super-resolution. In a test of their ideas, standard RGB imagery was converted to greyscale images. In the conversion process, each pixel of the original image was represented by two greyscale versions, which had random weighting coefficients applied to synthesise variations in spectral response. A super-resolution transform was then applied to recover the original colour pixels from the separate greyscale views. Cross-validation ensured that the data being predicted was not the same as that used to construct the transform. The technique was applied to 3-band imagery from Google-Earth and 4-band imagery from IKONOS.

3.2 Resolution Enhancement

The EMRS DTC is also concerned with the development of techniques that enhance the resolution abilities of passive imaging systems. Here, the need to compensate for the effects of atmospheric turbulence when imaging at long range is of importance. Lucky Imaging provides a means of defeating the effects of atmospheric turbulence, which would otherwise cause blurring, so limiting the range for recognition and identification in long-range ground-based imaging. Woods et al [11] have developed an efficient and robust solution based on measuring the optical phase aberration effects on transmission through the atmosphere rather than applying sophisticated processing algorithms to the entire image or processing large datasets of images. The technique is based on the use of a 'phase-diversity' metric (PDM) generated using a robust grating-based approach. The specially-designed grating located in the re-imaged pupil plane of the telescope provides for angular separation and defocusing of the phase-diversity images. The PDM metric is determined for small sub-frames of the image and the final images are re-constructed from an assembly of the best sub-frames. This metric has a noise response that is completely appropriate to lucky sub-frame selection and is insensitive to variations in image content, a known problem for image based metrics.

A team at QinetiQ [12] has also shown that it is possible to exploit sequences of images in which there is relative motion between sensor and scene/target, to provide step-change improvements in target acquisition, target identification and scene reconstruction performance. Their approach has provided benefit through the development of high dimensional Bayesian inference techniques supported by research in the image processing related disciplines of optical flow, track before detect, structure from motion and scene reconstruction. The algorithm is able to account for gradual depth variation across the scene geometry and out of plane rotations of target or scene.

3.3 Active Discrimination Techniques

Several groups have explored the feasibility of vibrometric imaging. This is another example of multi-functional active imaging, which allows the time-varying vibrometric signatures of targets to be superimposed on images of scenes. In a recent embodiment [13], a frequency modulated laser source is used for both the transmit beam and the local oscillator signal. The local oscillator is mixed with the received beam and the mixed signal detected by a detector array, but with a delay time substantially the same as the flight time of the radiation. Any variations in modulation of the source will be present in both the receive beam and local oscillator signal and will to a large extent cancel. The use of a delay also means that the detected intermediate frequency has a narrow bandwidth, so easing signal processing requirements and reducing the effects of source phase noise.

The detected signal therefore has an intermediate component representative of residual range and bulk Doppler effects and an AC component that contains the micro-Doppler frequencies characteristic of the target.

Range discrimination techniques can be used to provide additional information to support the identification of targets in the far field. Conventionally, targets are illuminated using a short-pulsed laser and the detector array used to image the returns is gated to exclude the processing of signals received from outside a given region of interest. By exploiting advanced read-out architectures in the detector array ROIC, Selex has shown that it is possible to record information from multiple range gates and to generate a 3D image of the scene from a single short laser pulse. At a practical level, such active imaging systems need to be used in conjunction with a passive IR surveillance sensor for cueing. Currently, separate camera systems are used to accomplish this goal, but as the technology evolves, it will be possible to combine this degree of functionality in a single aperture system.

By exploiting a time-correlated single photon counting technique, it has been shown [14] that 3D images of objects can be covertly obtained at ranges of 330m with a 3D spatial resolution of 5cm. Range ambiguities are avoided by transmission of non-periodic pulse trains and the correlation between the transmitted and received signals is used to determine time-of-flight to the target. Using a GHz VCSEL source, with GHz pulsed pattern generator and a repeated random pattern length of 96kbits it has been possible to achieve centimeter resolution at a distance of 330m.

There are similarities here with techniques being explored for quantum sensing, which also exploit correlation processes. In this case, the correlation being exploited is that between entangled photons, generally produced as a result of parametric down-conversion. Such processes usually entail laser pumping of non-linear crystals such as BBO, to produce degenerate biphotons. One of the entangled photon pairs is transmitted to the target whilst the other forms a reference. The return from the target is then correlated with the reference by interferometry. Various other schemes are also being explored for quantum sensing, including the so-called quantum ghost imaging process. This has been applied to the challenge of covert imaging using both entangled photons and photons arising from pseudo-thermal sources. Once again, the common requirement is for the exploitation of photon correlation techniques.

The pseudo-thermal source can be regarded as a classical electromagnetic wave whose photodetection statistics can be treated via the semi-classical theory of photodetection. It has been shown that ghost imaging can be accomplished with only one detector, such as a bucket detector that collects a single pixel of light reflected from the object. In fact it has been argued by Shapiro [15] that it should be possible to exploit an approach where the deterministic modulation of a cw laser beam could be used to create the field and then use diffraction theory to compute the intensity pattern that would have illuminated the pinhole detector in the usual lensless ghost-imaging configuration. Such a computational ghost imager could yield background-free images whose resolution and field of view can be controlled by choice of spatial light modulator parameters, and it can be used to perform 3D sectioning.

Whilst the basis of a diffractive computational imaging system has been demonstrated using coded aperture techniques through experiment in the visible band [16], it has more recently been applied to the infrared [17]. A significant development here has been the addition of simple lenses to increase the intensity of radiation incident on the detector array and to avoid higher diffraction orders being lost outside the footprint of the detector array. This provides significant advantage in improving signal-to-noise ratio at the detector, without compromising the other benefits of the coded aperture technique. Radiation from any point in the scene is still spread across several hundred elements, but this is also sufficient to simplify the signal processing required to decode the image. The benefits of such a system in providing resolution beyond the Nyquist limit imposed by the detector array have been clearly demonstrated and will have a major impact on the ability of such systems to track targets in cluttered scenes.

It is clear that there is a little way to go yet before such computational imaging systems can be fielded on a practical basis. Nevertheless, many of the challenges in the processing of signals emerging from the detectors have been addressed, which provide a degree of confidence in the level of performance likely to be achieved when such a system is used to track targets in urban scenes at resolution levels beyond the diffraction limit.

4. Biological Quantum Sensing Processes

Quantum effects have been postulated to have roles in a number of biological systems. Recently experimental results have demonstrated long-lived quantum coherence in bacterio-chlorophyll complexes [18] and in other bacteria-related reaction centres [19]. There may also be other examples of quantum effects such as those responsible for the magnetic navigation ability of some species of birds due to the quantum Zeno effect in a photo-responsive protein complex [20]. On the other hand there are several theories at work in describing processes of magneto-reception in birds. Some propose radical-pair mechanisms, where macromolecules are raised by photon absorption to excited singlet states, at which radical pairs are generated. By hyperfine interactions, singlet pairs may be converted into triplet pairs, with the yield depending on the alignment of the macromolecules to the axis of the magnetic field lines.

Irradiation experiments with different species of birds suggest a relationship between the wavelength of light employed and the ability of the birds to obtain directional information from the magnetic field. Recent work has shown that retinal cryptochrome-expressing neurons and a specific area of the fore-brain, show high neuronal activity when night-migratory songbirds perform magnetic compass orientation [21]. The findings strongly support the hypothesis that migratory birds use their visual system to perceive the reference compass direction of the geomagnetic field and that migratory birds ‘‘see’’ the reference compass direction provided by the geomagnetic field.

Whether such processes play a role in other organisms is a matter of debate. Certainly studies of ants, bees and beetles have revealed some remarkable sensing abilities. For example, Arendse [22] showed that mealworm beetles are able to use magnetic fields to orientate their body direction. Later studies [23] showed that light reception also plays an important part in ensuring replicable behaviour.

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