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Motion detection and stochastic resonance in noisy environments

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Abstract

Several motion detection schemes are considered and their responses to noisy signals investigated. The schemes include the Reichardt correlation detector, shunting inhibition and the Horridge template model. These schemes are directionally selective and independent of the direction of change in contrast. They function by using spatial information and comparing it at successive time intervals. A rudimentary noise analysis is performed on the Reichardt and inhibition detectors to compare their natural robustness against noise. Using these detectors, stochastic resonance (SR) is applied, which is characterised by an improvement in response when noise is added to the input signal. It is found that the performance of the detectors degrades with the addition of noise. Employing Stocks' suprathreshold SR, an improvement can be gained when considering a network of detectors. Furthermore, when using an incorrect threshold setting for the template model, SR can be displayed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Smart sensors; Motion detection; Collision avoidance; Insect vision; Stochastic resonance; Noisy sensory neural models; Noise

1. Introduction

In poor weather conditions, millimetre waves offer a much greater penetration over the visible spectrum through small dust particles (aerosols), rain and fog. Antenna arrays capable of detecting mm-waves can be constructed [1]. This design utilizes radiometry, which is the science of using passive detection techniques to detect background radiation. Unlike radar, which transmits a signal then receives the backscattered radiation, a radiometer only receives naturally occurring blackbody radiation. It is reasonable to expect then, in this passive detection system, the signals are inherently noisy. Thus, the noise must be taken into account when processing the antenna array signals for the desired application.

The primary application is for a collision avoidance sensor, that is, a motion detector. This has stemmed from earlier work that developed a single 'seeing chip' [2–4] based on insect vision. This functioned in the visible spectrum and implemented a simple 'insect template model' to detect motion [5–7]. The aim is to extend this to the mm-wave spectrum and utilize the noise to develop a robust mm-wave collision avoidance sensor.

A common belief is that addition of noise to a system always degrades the quality of the response; however, by use of the phenomenon of stochastic resonance (SR), this is not always true. Certain non-linear systems have shown that there is an optimal non-zero noise intensity which can be added to a system to improve the response [8]. Originally developed for periodic signals, SR has been extended to systems with either sub or supra-threshold broadband (aperiodic) signals [9].

Three motion detection schemes have been investigated and we have evaluated the effects of SR in the presence of noisy signals. The first is the Reichardt detector, which was the earliest explicit model in motion processing [10]. The second involves shunting inhibitory neurons [11], which originated from a neurophysiological model [12]. The last is the Horridge template model, which is based on the navigation mechanism that bees use, to navigate [13]. This is included for historical reasons, and also because of its simplicity to implement.

2. Motion detection schemes

In order for a scheme to detect motion, in a directionally selective way, certain minimum requirements must be satisfied; asymmetry, two inputs and a non-linear interaction [14]. Two inputs are necessary since motion is a vector, a single receptor could not distinguish a change in intensity coming from either the left or right. A non-linear interaction between the inputs is required; otherwise, all information about the temporal sequence is lost. This inhibits the sensor

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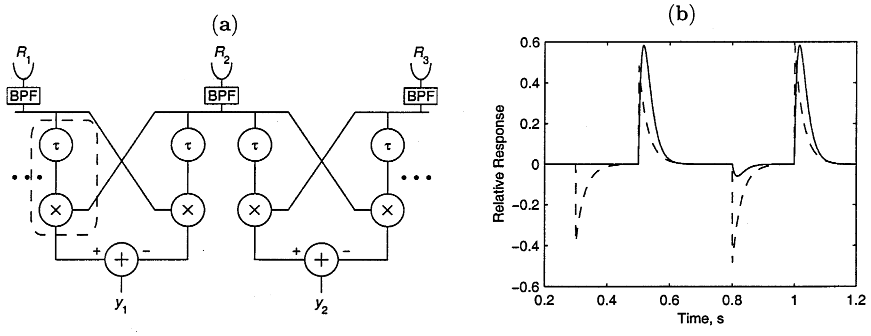

Fig. 1. (a) A section of the widefield Reichardt detector. (b)The response to two positive steps (0.5 and 1.0 s) with the BPF (solid line) and without (dashed line).

from being directionally sensitive. Finally, there must be some asymmetry between the two inputs; otherwise, the input receptors could be switched without affecting the output, giving no directional selectivity.

There are several broad categories of detection schemes, which stem from the basis of their conception. Biological schemes based on cellular mechanisms or neurophysiology can be divided into gradient and correlation type of models. Gradient schemes estimate motion by relating the changes in spatial and temporal intensity, whilst correlation schemes are essentially based on the common delay and compare systems. The other broad categories are the artificial schemes that take more engineering type of approaches.

Before going into details about the motion detection schemes, some criteria are established to determine the requirements of the schemes [11]:

- The sign of the response must indicate the direction of motion. This should be independent to the direction of change in contrast of the moving object.
- There should be no response to a stationary edge or a varying contrast.
- Ideally, it should be robust to noise.
- For an array of sensors, i.e. in the widefield, the position of the response should correspond to the moving edge. That is, spatially separated moving edges should each have a corresponding response.

The detectors that are considered in this paper are the Reichardt correlation detector, shunting inhibitory neuron and the Horridge template model.

2.1. Reichardt detector

Also called the correlation detector, it is one of the earliest biological motion detection systems based on the optomotor response of insects [10]. The Reichardt elementary motion detector (EMD) detects motion in one direction by comparing the signal from one receptor to a delayed signal from an adjacent receptor. The dashed box in Fig. 1(a) shows a single EMD. The comparison unit employs a simple multiplication, or correlation of the two signals. Due to the asymmetry of the EMD, there exists a preferred and a null direction. That is, the response to a stimulus moving in one direction has a larger magnitude (preferred direction) to the response of the same stimulus moving in the opposite direction (null direction). For the EMD highlighted in Fig. 1(a), the preferred direction is to the right and the null to the left.

Combining two EMDs tuned to opposite directions forms a bi-directional motion detector which is shown in Fig. 1(a) in the widefield configuration. Bandpass filters (BPF) are placed directly after the receptors to attenuate unwanted high frequency components in the response.

The delay stage, represented by τ, is modelled as an exponential decay, which is implemented as a first order low pass filter with the transfer function $H(s) = A/(s + A)$, where A is the cut-off frequency. This allows better integration of the delay stage into the biological modelling. The delay stage, along with the spatial separation of the receptors, allows tuning of the detector to different velocities.

The response of one of the local outputs (y_1 say) to a step input is shown in Fig. 1(b) by the solid line. This is briefly explained as follows. Consider a step with background luminance L that increases to $(1 + c)L$ whilst moving from left to right, where c is the contrast $(-1 \leq c \leq 1)$. The output of the BPF is a pulse and with appropriate tuning, the delay time corresponds to the time taken to move between receptors allowing the pulses to coincide at the correlation unit to produce a positive response. The differencing of the EMDs then determines the sign of the direction. If the pulse generated by the BPF has not decayed before the stimulus reaches the next receptor, the pulse tail interacts causing a small dip.

This dashed line in Fig. 1(b) is the response of the Reichardt detector when the BPFs are omitted. The two peaks reveal the interactive mechanism at work, namely an excitatory one. This means that, every time a change is incident on one receptor, neighbouring outputs are affected, usually with the opposite magnitudes as seen in Fig. 1(b). Once the signals have been bandpass filtered, the effect of the excitatory mechanism is reduced to a small dip. This was