IFF with the SpEcBar

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1. The Spatially-Encoded Bar Code

The Spatially-Encoded Bar Code (SpEcBar) uses distributed basis functions, such as sinusoids or wavelets, to encode a small number of bits of information in a pattern that can be applied as a patch to an object. We first describe the SpEcBar for one-dimensional signals.

Consider a *pattern* defined by $f(x) = \sum c_i \varphi_i(x)$, where the $\varphi_i(x)$ are orthogonal basis functions, such as sinusoids with integral wave numbers, i.e., $\sin(nx)$, or wavelets centered at a particular location, $W_{2^i}(x - x_0)$, which is a wavelet of scale 2^i centered at x_0. If the pattern is analyzed by a decomposition with the basis functions, $\langle f, \varphi_i \rangle$, then the coefficients c_i are recovered. On the other hand, a naïve observer viewing the pattern $f(x)$ will see a pattern with no particular significance.

Portions of the pattern may be obscured. With sinusoids, as long as the frequencies represented in the sum are sufficiently large, peaks in the spectral decomposition will be observed if enough cycles are represented in the observed portions of the pattern. Indeed, a sinusoid windowed by a function $w(x)$ results in a spectral response contribution of $\delta_\omega * \hat{w}$, which despite the blurring characteristics of $\hat{w}$, will still give a peak at ω. Normally, $\hat{w}$ will be a sum of sinc functions, and thus will have a sizable peak at 0, and thus the shifted function $\hat{w}(\cdot - \omega)$ will have a strong peak at ω.

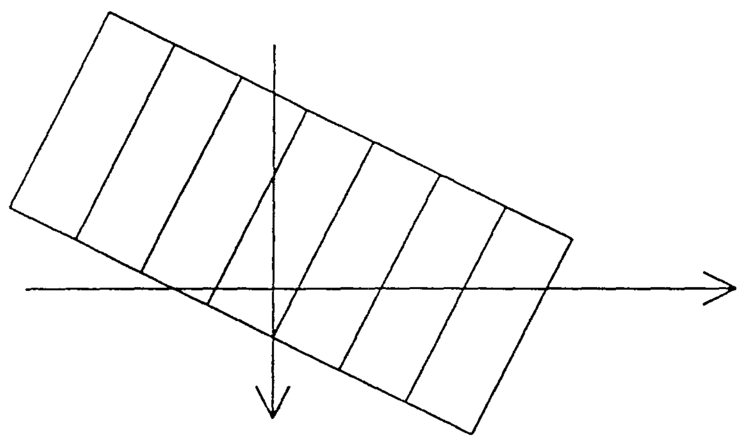
With wavelets, the same argument holds, but the spatial localization of the wavelet can be used to improve performance with respect to obscuration. Let $W_s(x)$ be a wavelet at scale s. The collection $\{W_{s_i}(x - x_{i,j})\}$ for a set of scales $\{s_i\}$ and for a set of spatial positions $\{x_{i,j}\}$ that depend on the scale s_i are orthonormal, and can thus form independent coding functions. Each function has essential spatial support that is localized around $x_{i,j}$. Thus the pattern $f(x) = \sum c_{i,j} W_{s_i}(x - x_{i,j})$ encodes the information in the coefficients $\{c_{i,j}\}$, and by using equal values for different spatial positions at the same scale, $c_{i,j} = c_{i,j'}$ for $j \neq j'$, a collection of coefficients are redundantly encoded by the pattern, and can be extracted by a wavelet decomposition, providing a sufficient portion of the pattern is unobscured. The set of frequencies encoded by the wavelets $\{s_i\}$ form a dyadic sequence, so that typically $s_i = 2^i$.

For a two-dimensional pattern, we use a one-dimensional SpEcBar and build a 2-D pattern by encoding the same information on each horizontal slice. One way to do this is to repeat the same function on each horizontal slice, creating a vertically-striped SpEcBar. In this case, the 2-D pattern g will be given by $g(x,y) = f(x)$ in a rectangular patch. However, there is no requirement that the SpEcBar be vertically constant. More generally, we may set

$$g(x,y) = \sum c_i(y) \cdot \varphi_i(x),$$

where the $c_i(y)$ are constant for the particular indices i that encode the information that we wish to convey in the SpEcBar, i.e., $c_i(y) \equiv a_i$ for a subcollection of indices i. The coefficients that are not in the subcollection are allowed to vary. In either case, we will use $f(x)$ to denote an arbitrary horizontal slice through the SpEcBar, with the understanding that $f(x)$ may vary for different slices, but will always encode the same information.

In order to extract information from a two-dimensional SpEcBar, we require that a linear scan be obtained and digitized, where the scan intersects the SpEcBar at an angle no greater than 45°. This can be accomplished by scanning the scene in a raster-scan fashion twice, once from left-to-right and top-to-bottom, and the next time top-to-bottom and left-to-right. For each linear scan, we obtain a function $h(x)$ representing the scanline data for that slice.



We examine each linear scan to see if the SpEcBar code can be extracted from the corresponding function $h(x)$.

Since the scanline slice is not necessarily a horizontal slice through the SpEcBar, the function $h(x)$ will be a distorted version of the pattern $f(x)$. However, the distortion is necessarily a dilation:

$$h(x) = f(t \cdot x),$$

where t is a dilation factor related to the slope of the scanline through the SpEcBar.

Because of the dilation, the decomposition of h will not directly yield the desired coefficients. However, both the sinusoidal basis functions and the wavelet basis functions have the property that dilations of the basis functions are in the same class as the original set of basis functions, although they may not precisely equal one of the discrete collection of basis functions that are used in the orthonormal expansion. For sinusoids, we have that $\sin(t \cdot nx)$ is a sinusoid with wave number $n \cdot t$, and for wavelets, $W_s(t \cdot x) = W_{t \cdot s}(x)$, which is a wavelet at scale $t \cdot s$. It can easily happen that the resulting wave number is non-integer or the scale factor for the wavelet is not a power of two. However, through numerical processing techniques it is nonetheless possible to extract the encoded information.

Although it is not necessarily the most efficient method, one way to handle the dilation is to simply decompose the observed scanline data $h(x)$ at various dilation scales, so that $h(x / t_k) = \sum b_{i,k} \varphi_i(x)$ yields a collection of coefficients $\{b_{j,k}\}$ for a set of candidate $\{t_k\}$. Because of the closed nature of the basis functions, it is not required that the exact value of t_k used in one of the candidate dilations equals the value of t representing the scan angle. Sinusoids are particularly advantageous here, since it is only required that t / t_k be close to integral.

The method of encoding information in a SpEcBar requires that:

- A SpEcBar code be recognized when it is seen;
- A SpEcBar code is not likely to be seen by chance;
- Some small amount of additional information is carried along with the SpEcBar code.

A method for accomplishing this using sinusoids would choose, say, four spectral bands at which a high spectral component is recorded, together with two other bands to encode information. The presence of large coefficients for the four bands encodes the presence of the SpEcBar. Neither phase nor magnitude information is important, save for large magnitudes of all four frequencies. A number of other designated spectral frequencies can then encode information. Both the amplitude and phase of the coefficients to these bands can, in a quantized fashion, yield information. The amplitudes can be measured relative to the amplitudes of the four identifying spectral components, and two bits of information can likely be carried in each amplitude. Likewise, the phase component can likely carry another two bits. Depending on the resolution of the system observing the SpEcBar, a encoded spectral lines might encode a sufficient number of bits to give a unique identifier from among millions of possible numbers.

With wavelets, the situation is slightly different—there is no phase information, but the coefficients can be more informative. However, because of the spatial redundancy and the dyadic distribution of the frequencies, there is likely to be fewer available spectral lines to choose from, so that more bits should be carried on each channel. Information can be spatially encoded using the wavelet-based SpEcBar, although there is then potentially a loss of information due to partial obscuration.

Suppose that a total of ten spectral lines carry information in a SpEcBar. In order to properly hide the SpEcBar in the non-designated lines, there should be many more available lines. For sinusoids, we might insist that there be 64 lines available, which means that 128 digitized samples should fall on the SpEcBar. If the SpEcBar is a small patch, then this means that highly accurate close-up observation is required. However, if the SpEcBar is large enough that the frequency components of the object of interest fall in the same range as the designated frequencies in the SpEcBar, then we can assert that the SpEcBar is readable whenever the object is discernible.

2. Combat Identification using the SpEcBar

For IFF (or Combat Identification) applications, the SpEcBar Code can be used to paint decals on a vehicle (or even a helmut) that can be observed, scanned, and analyzed in order to obtain an identification number. By using removable (or paste-on) decals, codes can be changed daily. The interrogator scans and locates a decal, digitizes the reflectivity information, and processes the information using 1-D transformations. The scanning can be done numerically using a digitized array from a focal plane array, or can be done using a single-pixel sensor that scans the target using a raster scan or random linear scan fashion.

There are two possible modes of operation. In the Active SpEcBar system, the interrogator paints the target with a scanning beam, and observes the reflection using a notch filter receiver. The spectral response of the reflected beam will be attenuated by the width of the spot size on the SpEcBar, so that the spot size must be kept small with respect to the designated encoding frequencies on the patch.

In the Passive SpEcBar system, the patch is observed using reflected background radiation, and a sensor/digitizer observes the object and performs numerical processing. In the passive system, the SpEcBar decal might well encode the information using variable IR reflectivity, so that the observing sensor is a FLIR (which can optionally be a one-bit gimbaled FLIR).

The required one-dimensional FFTs or wavelet decomposition's are easily performed in real time using DSP chips. Note that there is no requirement for a 2-D spectral decomposition. The only limiting requirement is that there must be a sufficient number of samples on the SpEcBar so as to both accurately locate the designated spectral bands, and so that the designated bands can be hidden in enough other lines so as to make the background marking inconspicuous.