

Saliency, Scale and Image Description

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Abstract

Many computer vision problems can be considered to consist of two main tasks: the extraction of image content descriptions and their subsequent matching. The appropriate choice of type and level of description is of course task dependent, yet it is generally accepted that the low-level or so called early vision layers in the Human Visual System are context independent.

This paper concentrates on the use of low-level approaches for solving computer vision problems and discusses three inter-related aspects of this: saliency; scale selection and content description. In contrast to many previous approaches which separate these tasks, we argue that these three aspects are intrinsically related. Based on this observation, a multiscale algorithm for the selection of salient regions of an image is introduced and its application to matching type problems such as tracking, object recognition and image retrieval is demonstrated.

Keywords

Visual Saliency, Scale Selection, Image Content Descriptors, Feature Extraction, Salient Features, Image Database, Entropy, Scale-space.

1 Introduction

The central problem in many computer vision tasks can be regarded as extracting ‘meaningful’ descriptions from images or image sequences. These descriptions may then be used to solve matching or correspondence problems such as object recognition, classification or tracking. The key issues

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are of course what is ‘meaningful’ and what form the descriptions should take. In general, the answers to both of these are context specific. Yet it seems that the Human Visual System (HVS) is capable of solving a variety of vision tasks with apparent ease and reliability, and if generally accepted models of the human visual system are to be believed, it does so with a common front end (retina and early vision).

It is generally agreed that the HVS uses a combination of image driven data and prior models in its processing. Traditionally, different groups within the computer vision community have tended to place emphasis on one of these two extremes, but it is rare to find complete systems that rely solely on a single methodology. Although the precise nature of this combination within the HVS remains unclear, it is widely accepted that early or low-level vision is quite independent of context.

One of the main models for early vision in humans, attributed to Neisser (1964), is that it consists of pre-attentive and attentive stages. In the pre-attentive stage, ‘pop-out’ features only are detected. These are local regions of the image which present some form of spatial discontinuity. In the attentive stage, relationships between these features are found, and grouping takes place. This model has widely influenced the computer vision community (mainly through the work of Marr (1982)) and is reflected in the classical computer vision approach - feature detection and perceptual grouping, followed by model matching/correspondence.

To date, there have been difficulties in realising robust vision systems based purely on this model. The problems seem to arise mainly in the grouping stage. For the matching stage to work effectively, the grouping must reflect the structure of the object(s) under test. However, in the general case it seems difficult to achieve this purely from image data, without additional context-specific constraints. Segmentation algorithms are often used to solve low-level pixel or feature grouping problems. Although significant progress has been made in the analysis and formalisation of the segmentation problem, for example the MDL approach of Leclerc (1989), as used in Region Competition by Zhu and Yuille (1996), it remains notoriously difficult in the general case. For example, in the case of object recognition, it seems necessary to select the correct parts of an image to extract descriptions from, without first ‘knowing’ where and what the object is; that is, it is necessary to know which pixels belong to the object of interest.

Finding the optimal segmentation is difficult because the search space of possible pixel groups is too large, especially in algorithms that use multiple feature maps and so a sub-optimal search is used to make the problem tractable. Also, no single definition of segmentation (e.g. piecewise homogeneous intensities) suffices in practice and the automatic model selection problem is difficult to solve.

Recently, it has been suggested that purely local information could be sufficient to describe image content, (Schiele, 1997, Schmid and Mohr, 1997). Motivated primarily by the approach taken by Swain and Ballard (1995), Schiele (1997) has demonstrated very good object recognition and classification performance using local appearance descriptors without perceptual grouping of any kind. The method works by building multi-dimensional histograms for local feature responses across the image at multiple scales. The object is identified by matching these histograms to those stored in the database. The proposed framework achieves good recognition rates of objects in cluttered scenes, although in their examples, the clutter comprises other objects within the database rather than arbitrary ‘background’.

There are, however, limitations to a purely local approach. One can think of many instances where the structure of the features plays a significant part in the description of the object. For example, objects such as computer keyboards that comprise tessellated copies of local features. Another problem with the Schiele algorithm is that position information is not recovered, since no correspondence is calculated between the model and the image. In order to address this problem, Schiele proposes an extension of the algorithm based on the observation that certain feature locations of the object under test are more discriminating or *salient* than others. These could be used to identify possible locations of the object within the scene. Furthermore, by looking for a network of such salient points, it may be possible to resolve ambiguities which the unstructured local approach cannot. This idea was not implemented at the time of the thesis, but demonstrations of the principle were given.

In this paper, we investigate the use of low-level local approaches to vision tasks that involve correspondence and matching problems. We discuss three intimately related aspects of the problem: saliency, scale and description; and introduce a novel algorithm to create a hierarchy of salient regions that operates across feature space and scale.

The paper is organized as follows. In section 2 we introduce the idea of Visual Saliency and briefly review the approaches proposed in the literature to define it. We then introduce Gilles’ (Gilles, 1998) idea of using local complexity as a measure of saliency. In section 3 we report results using this method on a range of image source material ¹, and identify a number of limitations and problems with the original method. Having identified scale as a fundamental problem, Section 4 discusses this issue and a novel algorithm for assessing the saliency of local image regions is introduced which operates over feature space and scale. In section 5, we introduce the idea of identifying volumes in saliency space to improve robustness. We demonstrate the operation and

¹Gilles was primarily interested in the matching of aerial images.

properties of the algorithm (such as robustness to scale) on a number of simple example applications in section 6. In these examples, we have deliberately used a minimal set of prior assumptions and omitted enhancements of the basic method, in order to highlight the performance of our technique. For example, in the surveillance sequence experiment we have not assumed a fixed camera nor a fixed ground plane despite these being reasonable assumptions to make. Also, the addition of a Kalman or Condensation (Blake and Isard, 1997) tracker to the method would further improve the performance of the method; we are currently investigating the combination of these methods with our algorithm and will report results in a future paper. Finally, in section 7 we discuss the relationship between the described approach to low-level saliency and the problem of image content description.

2 Visual Saliency

Visual saliency is a broad term that refers to the idea that certain parts of a scene are pre-attentively distinctive and create some form of immediate significant visual arousal within the early stages of the HVS. See figure 1. The term ‘pop-out’ (Julesz, 1995) is used to describe the visual saliency process occurring at the pre-attentive stage. Certain visual primitives are immediately perceivable - they ‘pop-out’. (Treisman, 1985) reports on a number of experiments that identify which visual features ‘pop-out’ within the HVS.

Numerous models of human visual saliency (sometimes referred to as visual search or attention) have been offered in Cognitive Psychology and Computer Vision. However, the vast majority have tended to be only of theoretical interest and often in those cases that were implemented, only synthetic images were used. In contrast, we limit our discussion here to work that has been tested on real images. A good review may be found in (Milanese, 1993).

The idea of saliency has been used in a number of computer vision algorithms, albeit implicitly. The early approach of using edge detectors to extract object descriptions embodies the idea that the edges are more significant than other parts of the image. More explicit uses of saliency can be divided into those that concentrate on low-level local features (Schmid et al., 1998), and those that compute salient groupings of low-level features (Sha’ashua and Ullman, 1988); though some approaches operate at both levels (Milanese, 1993). This paper focuses on the former, since the latter is more a task of perceptual grouping.

2.1 Geometric features

One popular approach is the development of so-called Interest point detectors. These tend to be based on two-dimensional geometric features often referred to as Corners ². Schmid and Mohr (Schmid and Mohr, 1997) select Interest points using the Harris Corner detector (Harris and Stephens, 1988), and then extract descriptors at these locations for an image retrieval application. Corner features are used because they are local (robust to occlusion) and are relatively stable under certain transformations. It is also claimed that they have high ‘information content’. In (Schmid et al., 1998) the authors compare different Interest point detectors for their repeatability and information content; the latter is measured by considering the entropy of the distribution of local grey-value invariants taken around the detected Interest point.

Early Interest point detectors were commonly applied at the resolution of the image and hence did not have an inherent scale parameter. Later methods however, were implemented in a multiscale framework. Examples of such techniques include coarse to fine tracking (Mokhtarian and Suomela, 1998) and analysis of local extrema in scale-space (Lindeberg, 1994). Deriche and Giraudon (1993) use a computational model of corner behaviour in a linear scale-space to extract and accurate estimate of corner position.

Often, systems using Interest point approaches extract descriptors at a number of scales using Local Jets (Koenderink and van Doorn, 1987). However, such scales are arbitrary relative to the scale of the detector. For example, Corner features are often used to estimate correspondences to solve problems such as camera calibration. Correlations between pairs of local image patches around the Corners are used. Once again the sizes of these image patches, that is to say their scale, tend to be arbitrary. On the contrary, we argue that scale is intimately related to the problem of determining saliency and extracting relevant descriptions. In some recent work (Dufournaud et al., 2000) the authors link the Interest point detection scale to the description scale. However, this method does not address the problem of comparing saliency over different scales.

We seek a more general approach to detecting salient regions in images.

2.2 Rarity

Naturally, saliency implies rarity. However, as argued by Gilles (Gilles, 1998) the converse is not necessarily true. If everything was rare then nothing would be salient. Gilles also points out another problem with rarity-based saliency measures; ‘rarity’ is intrinsically defined by the method

²Note, these operators do not exclusively select features that are perceived to be the corners of objects; rather, they compute sets of zero measure typified by their peaked autocorrelation.

by which it is measured. If highly discriminating descriptors are used, then everything tends to be rare. If on the other hand the descriptors are very general, then nothing tends to be rare. Setting the appropriate level is difficult in general.

There are, however, a number of examples that use this approach. The technique suggested by Schiele (Schiele, 1997), is based on the maximisation of descriptor vectors across a particular image. Schiele states that:

These salient points are literally the points on the object which are almost unique. These points maximise the discrimination between the objects.

In his recognition algorithm, Bayes' formula is used to determine the probability of an object o_n given a vector of local measurements m_k :

$$p(o_n | m_k) = \frac{p(m_k | o_n)p(o_n)}{p(m_k)} \quad (1)$$

where

- $p(o_n)$ is the prior probability of the object o_n
- $p(m_k)$ is the prior probability of the filter output combination m_k
- $p(m_k | o_n)$ is the probability density function of the measurement vector of object o_n

The idea is that maximisation of $p(o_n | m_k)$ over all filter outputs across the image provides those points which best describe the image (in terms of uniqueness). The higher the value of $p(o_n | m_k)$ for a given point and neighbourhood in an image, the better that descriptor is for distinguishing that specific image from all other images within the database; in other words it is a measure of uniqueness. In order to use this method, the prior probability $p(m_k)$ must be estimated from the database..

In a related method, Walker et al in (Walker et al., 1998a) identify salient features for use in automated generation of Statistical Shape/Appearance Models. The method aims to select those features which are less likely to be mismatched. Regions of low density in a multidimensional feature space, generated from the image, are classed as highly salient. In (Walker et al., 1998b) the method is extended to work with multiple training examples.

2.3 Saliency as Local complexity

Gilles (Gilles, 1998), investigates salient local image patches or 'icons' to match and register two images. Specifically, he was interested in aerial reconnaissance images. Motivated by the pre-attentive and attentive vision model of human attention, Gilles suggests that by first extracting

the locally salient features (analogous to pop-out features) from each of a pair of images, then matching these, it is often straightforward to establish the approximate global transform between the images. If saliency is defined locally, then even gross global transforms do not affect the saliency of the features. Once the approximate transform has been found, a global matching method may be used to fine-tune the match without the matching algorithm becoming trapped in local minima (assuming of course that the salient features enable the gross match to be sufficiently accurate).

Gilles defines saliency in terms of local signal complexity or unpredictability; more specifically he suggests the use of Shannon entropy of local attributes. Figure 2 shows the local intensity histograms from various image segments. Areas corresponding to high signal complexity tend to have flatter distributions hence higher entropy ³.

More generally, it is the high complexity of a suitable descriptor that can be used as a measure of local saliency. Given a point \mathbf{x} , a local neighbourhood R_X , and a descriptor D that takes on values $\{d_1, \dots, d_r\}$ (e.g. in an 8 bit grey level image D would range from 0 to 255), local entropy is defined as:

$$H_{D,R_X} = - \sum_i P_{D,R_X}(d_i) \log_2 P_{D,R_X}(d_i) \quad (2)$$

where $p_{D,R_X}(d_i)$ is the probability of descriptor D taking the value d_i in the local region R_X .

The underlying assumption is that complexity in real images is rare. This is true except in the case of noise or self-similar images (e.g. fractals) where complexity is independent of scale and position.

3 Initial results

Motivated by the work of Gilles, we investigated the use of entropy measures to identify regions of saliency within a broad class of images and image sequences. Such salient regions are used to extract descriptions which could then be used to solve vision problems necessitating matching or correspondence. In this section, we summarise the results of applying the original Gilles technique to a range of different types of image source material.

3.1 Image source content

Gilles was primarily interested in single, still grey-level aerial images, whereas we are interested in colour image sequences containing a wide range of natural and man-made content. In general,

³Histograms are not confined to intensity; they may be any local attribute such as colour or edge strength, direction or phase.

aerial images contain features over a relatively small range of scales, and they exhibit little depth variation. Consequently, in many cases, aerial images can be treated as two-dimensional. In contrast to this, the images we are interested in contain features across a large range of scales. This is partly due to the nature of the objects themselves and partly due to the significant depth variation within the scene.

The unmodified Gilles algorithm was applied to the following three sequences :

- DT. A surveillance-type sequence at a traffic junction taken with a fixed camera. Sequence from KOGS/IAKS Universität Karlsruhe ⁴
- Vicky. A sequence of planar human motion (walking) against a primarily textured background in a park area taken with hand-held camcorder. Contains a free hand camera pan.
- Football. A sequence with multiple moving objects against a primarily textured background. Contains a camera zoom.

These sequences can be obtained from <http://www.robots.ox.ac.uk/~timork>.

3.2 Results and observations

Figure 3 contains sample frames from the processed sequences. The superimposed squares represent the most salient ‘icons’ or parts of the image; the size of the local window or scale and threshold used were selected manually to give the most satisfactory results. In general, the results are encouraging, with the algorithm selecting areas that correspond well to perceptually salient features. In the DT sequence this mostly coincided with the cars; in the Vicky sequence, the person’s head and feet. However, we encountered a number of problems. First, the scale (the size of the local region over which the entropy is calculated) is a global, pre-selected parameter. The global scale model is only appropriate for images that contain features existing over small ranges of scale, as is the case for aerial images. The limitations of the single scale model can be seen in the DT sequence in figure 3, where the scale is clearly inappropriate for the pedestrians and the road markings. Furthermore, this parameter should ideally be selected automatically. Gilles suggested a simple algorithm that could automatically select a single global scale by searching for peaks in average global saliency for increasing scales. This was useful in his application for identifying appropriate scales to be used between pairs of aerial images that had been taken at different heights, but would be of limited

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use in the general case where scale variations are much larger. As acknowledged by Gilles in his thesis, a local scale selection method is needed.

Another problem arises with highly textured regions that contain large variations in intensity. An example can be seen in the Vicky sequence frame in figure 3 where many icons reside (over time, rather unstably) on the trees and bushes. Although such regions exhibit complexity at the scale of analysis, large regions do not correspond to perceptually salient features at that scale.

We found that the algorithm is also sensitive to small changes and noise in the image. The positions of the icons rarely remain stable over time on a salient feature; rather, they oscillate around it. In a separate experiment, we repeatedly applied the algorithm on the same frame but with independent Gaussian noise added at each iteration to establish how much of the instability was due to noise and how much due to movement in the scene. We found that noise affected the positions of the icons significantly even though the positions of the features themselves had not changed.

The Gilles method picks single salient points in entropy space to represent salient features. However, it is unlikely that features exist entirely within the isotropic local region and hence several neighbouring positions are likely to be equally salient. In such a case, the locally maximum entropy from frame to frame could be a result of noise rather than underlying image features. Choosing salient *regions* rather than single salient *points* would reduce the likelihood of this occurring. Incorrect local scale would further compound this problem.

The next section presents our work which builds on the ideas of Gilles, by addressing the above discussed shortcomings of the original method.

4 Scale selection

In Gilles' original method, the local scale, that is to say the size of the local neighbourhood over which the PDF of the descriptor is estimated, was a pre-selected fixed parameter. As noted earlier, the algorithm that was proposed for the global selection of this value worked well for aerial images, but a local scale method is required for a wider range of image content. It has long been recognised that multiscale representations are necessary to completely represent and process images (more generally signals of any kind), and there is a wealth of work relating to this issue. We next briefly review this area.

4.1 Multiscale representations

Linear scale space theory (Koenderink, 1984, Lindeberg and ter Haar Romeny, 1994, Witkin, 1983) provides a mathematically convenient method to generate representations of images at multiple scales. The same framework also deals with the problem of well-posed differentiation of discrete images at specific scales. Justifications for the use of Gaussian kernels are derived from (amongst others) causality and extrema reduction. It is very widely used as a framework for multiscale signal processing. Efforts to deal with one of its significant shortcomings, namely edge blurring at large scales, have led to non-linear and anisotropic methods. Perona and Malik's (Perona and Malik, 1988) method weights the diffusion by an edge significance metric; Weickert's Diffusion Tensor (Weickert, 1997) improves on this by allowing diffusion along edges but not across them. Generally however, these have to be implemented as discrete approximations to differential equations. They tend to be slow and the mathematical relations between time and scale are less tractable than in the linear case, although some progress towards unifying these has been made by Alvarez et al. (1992).

Wavelet representations are an alternative multiscale representation. They are also very well researched and widely used, and have the benefit of being able to localise well in both scale and space. It has been claimed that since wavelets constitute an orthogonal basis they do not satisfy one of the requirements of a true scale-space - that it should be possible to establish relations over scale (ter Haar Romeny, 1996). This may be true of the Wavelet coefficients themselves which represent the detail or high-pass versions of a signal (at a certain scale range), but the reconstruction can be made to any arbitrary scale by successively summing these to the approximation or low-pass signal. In fact the relationship between Wavelet and Gaussian based scale-spaces is quite strong. The Gaussian diffusion methods operate as low-pass filters smoothing the original signal, whereas the Wavelet based methods are based on band-pass filters (through successive high and low pass operations). Many Gaussian diffusion-based scale spaces consider the difference between scales as part of the processing; an early example can be found in (Burt and Adelson, 1983). This Difference of Gaussian approximates the Laplacian pyramid which can be generated using the well known Marr-Hildreth Mexican hat edge detector (Marr and Hildreth, 1979) - an early form of Wavelet (Mallat, 1998).

Scale space representations enable us to analyse the signal of interest at different scales, however they do not tell us which of these scales we should use in subsequent processing. We discuss this problem next.⁵

⁵We do not advocate the use of a one particular scale space representation in our work. Rather we are interested

4.2 Scale Selection

There are a number of separate issues to address. First, which scales are optimal and can these be selected automatically? Second, the definition of saliency should be extended to work across scale as well as feature space. Scale is an implicit part of the saliency problem. In other words, can we compare saliency over scale as well as in feature space?

There are fewer examples of scale selection in the literature compared to multiscale representations. The widely adopted approach is to apply some kind of processing at multiple scales and use all of these results; an example is (Schiele, 1997). However this leaves scale as a free parameter which increases the search space for matching problems. In their image retrieval application, for example, Schmid and Mohr use local configurations of features to reduce the number of false positive matches (Schmid and Mohr, 1997). Furthermore, this approach increases the amount of stored data.

It is known that features exist over a range of scales, hence can best be observed over that range. Lindeberg (1993, 1994) suggests that for Geometric image descriptors, the ‘best’ scale can be defined as that at which the result of a Differential operator is maximised (from a signal processing point of view this can be interpreted as maximising signal-to-noise). This idea was shown to improve object recognition in (Chomat et al., 2000). It seems sensible then to select scales at which the entropy is maximised. This approach is intuitively plausible but only addresses the first of the issues discussed at the beginning of this section. It does not provide any information regarding the scale-space behaviour of the saliency of a given feature. The left-hand diagram in Figure 4 shows the salient regions found by maximising entropy versus scale. The resulting features do not represent the image objects well; if used in a matching task the selected features would not produce unique correspondences.

Different features can produce maxima or peaks in entropy, for increasing scales, of different widths. One important question is: which is the more salient - a feature that is observed over a large range of scales (a wide peak) or one that observed over a small range? In (Bergholm, 1986) Bergholm tracks edges over multiple scales, an idea originally suggested by Witkin (Witkin, 1983); those that survive over many scales are deemed to be the more significant. This is appropriate for edges because although the edge has a specific scale associated with it in the perpendicular direction, it does not in the tangential direction.

in scale selection and the extension of saliency to operate over scale. We have used a circular top-hat sampling kernel to generate our scale space for reasons of simplicity, rotational invariance (in the image plane) and because it does not alter the statistical properties of the local descriptor.

However, in our case we are looking for local salient features based on what is complex as defined by entropy (predictability). Complexity is assumed to be rare. If an image was complex and unpredictable at all spatial locations and scales, then it would either be a random image or fractal-like. Features that exist over large ranges of scale exhibit self-similarity, which in feature space, we regard as non-salient. Following the same reasoning, extending our saliency measure to scale, rather than adopting the conventional view of multi-scale saliency, we prefer to detect features that exist over a narrow range of scales.

Our method works as follows: for each pixel location, we choose those scales at which the entropy is a maximum, or peaked, then weight the entropy value at such scales by some measure of the self-dissimilarity in scale-space of the feature.

Since we select scales at which the entropy is peaked, the peak width could be used directly. However it is difficult to measure this consistently. Also, there are many exceptional cases that result in slow computation. Instead, we use the statistics of the local descriptor over a range of scales around the peak to measure the degree of self-similarity. There are many methods by which PDFs can be compared, for example the Kullback contrast, Mutual Information or χ^2 . However, for simplicity we have used the sum of absolute difference of the grey-level histogram. Our proposed saliency metric \mathcal{Y} , a function of scale s and position \vec{x} , becomes:

$$\mathcal{Y}_D(\vec{s}, \vec{x}) \triangleq \mathcal{H}_D(\vec{s}, \vec{x}) \times \mathcal{W}_D(\vec{s}, \vec{x}) \quad (3)$$

where entropy \mathcal{H}_D is defined by:

$$\mathcal{H}_D(s, \vec{x}) \triangleq \int_{i \in D} p_D(s, \vec{x}) \log_2 p_D(s, \vec{x}) .di \quad (4)$$

and where $p_D(s, \vec{x})$ is the probability density as a function of scale s , position \vec{x} and descriptor value i which takes on values in D the set of all descriptor values. The weighting function, $\mathcal{W}_D(s, \vec{x})$, is defined by:

$$\mathcal{W}_D(s, \vec{x}) \triangleq s \cdot \int_{i \in D} \left| \frac{\partial}{\partial s} p_D(s, \vec{x}) \right| .di \quad (5)$$

The vector of scales at which entropy is peaked, \vec{S} , is defined by:

$$\vec{S} \triangleq \left\{ s : \frac{\partial^2 \mathcal{H}_D(s, \vec{x})}{\partial s^2} < 0 \right\} \quad (6)$$

Jagersand in (Jägersand, 1995) and Winter in (Winter et al., 1997) have also used the notion of dissimilarity between consecutive scales to determine significant features. However, we define a saliency metric applicable over both feature space and scale simultaneously, hence can compare

the saliency of different features occurring at different spatial locations and scales. The right-hand diagram in Figure 4 shows the effect of applying the scale dissimilarity weighting on simple synthetic example. The value of entropy has been weighted by the sum of absolute difference of the histograms at the peak. The addition of a scale-space measure has enabled the method to correctly capture the most salient features and scales. In a matching task, these features are much better, that is produce fewer incorrect matches, than those found using maximised entropy alone (shown in the left-hand diagram in figure 4).

4.3 The Algorithm

The proposed algorithm works as follows:

1. For each pixel location \vec{x} :
 - (a) For each scale s between s_{min} and s_{max} :
 - i. Measure the local descriptor values within a window of scale s .
 - ii. Estimate the local PDF from this (e.g. using histograms).
 - iii. Calculate the local entropy (\mathcal{H}_D).
 - (b) Select scales ($\vec{\mathcal{S}}$) for which the entropy is peaked ($\vec{\mathcal{S}}$ may be empty).
 - (c) Weight (\mathcal{W}_D) the entropy values at $\vec{\mathcal{S}}$ by the sum of absolute difference of the PDFs of the local descriptor around $\vec{\mathcal{S}}$.

The algorithm generates a space in \mathcal{R}^3 (two spatial dimensions and scale) sparsely populated with scalar saliency values.

Figure 5 shows the results of the new algorithm applied to various images. In these examples, the histogram of local grey-level values is used as the descriptor and a global threshold is applied. In the original single scale method, a significant problem was that of textures and other self-similar texture-like areas such as trees in the background of outdoor scenes. These would be measured as highly salient because they tend to contain a large number of grey-level values in roughly equal proportion. However, because they are largely self-similar, the whole area tends to be of approximately equal saliency, leading to unstable salient icons. Furthermore, our assumption that complexity is rare (in spatial dimensions) does not hold in this case and many self-similar icons are chosen leading to a poor description of the image.

In the new algorithm, we search for saliency in scale-space as well as spatial dimensions, therefore we can easily handle notions of self-similarity and saliency in the same framework. In figure 5,

we can see that the large areas of texture do not affect the choice of the most salient parts. In the first example (top-left) in figure 5, the grey-level range of the radial shaded areas is very similar to that of the textured background.

In essence, the method searches for scale localised features with high entropy, with the constraint that scale is isotropic. The method therefore favours blob-like features. Alternatively, we can relax the isotropic requirement and use anisotropic regions. This has the drawback of increasing the dimensionality of the saliency space. Moreover, the relatively simple notion of scale as a single parameter is lost. However, for some features, such as those with local linear structure, this may be necessary to correctly characterise local scale behaviour. In this case two scales may be used to analyse the feature; one tangential and one perpendicular to the direction of the feature. This is the subject of ongoing research, and in this paper we concentrate on isotropic features. Such features are useful for matching because they are locally constrained in two directions. Features such as edges or lines only locally constrain matches to one direction (of course depending on their length).

It should be noted however, that the method does detect non blob-like features, but these are considered less salient than their isotropic equivalents. In the case of linear structure, this is because there is a degree of self-similarity in the tangential direction. The selected scale is determined predominantly by the spatial extent of the feature in the perpendicular direction. The spatial extent in the tangential direction of such anisotropic regions could be analysed by a post-processing grouping algorithm. In solving the correspondence problem, this ranking is somewhat desirable as it reflects the information gained by matching each type of feature.

5 Salient Volumes

The original Gilles algorithm selects the most salient (high entropy value) *points* in entropy space as generated from the image. These points represent small image patches in the original image function, the sizes of which are determined by the scale of the entropy analysis. These image patches are referred to (in Gilles' thesis) as icons.

Robustly picking single points of entropy maxima relies on the persistence of these points in various imaging conditions, such as noise or small amounts of motion. It is known that the presence of noise in the image acts as a randomiser and generally increases entropy, affecting previously low entropy values more than high entropy values. However, the effect of noise also depends greatly on the shape of the local entropy surface around the maximum. Furthermore, our new saliency

metric generates a \mathcal{R}^3 space (2 spatial dimensions and scale) and so we must extend our selection method to work with this.

A more robust method would be to pick *regions* (or *volumes* in \mathcal{R}^3) rather than points in entropy space. Although the individual pixels within a salient region may be affected at any given instant by the noise, it is unlikely to affect all of them in such a way that the region as a whole becomes non-salient.

Some form of clustering algorithm would be appropriate for this task. However standard methods such as K-means usually require the number of clusters to be defined a-priori. Furthermore, they usually demand completeness, that is, they assume that everything is to be grouped into one of the clusters. In our saliency space only some of the points should be clustered, many of the low saliency points are due to noise or textures.

It is also necessary to analyse the whole saliency space such that each salient feature is represented. A global threshold approach would result in highly salient features in one part of the image dominating the rest. A local threshold approach would require the setting of another scale parameter.

We have developed a simple clustering algorithm to meet these two requirements. It works by selecting highly salient points that have local support - that is, nearby points with similar saliency and scale. Each region must be sufficiently distant from all others (in \mathcal{R}^3) to qualify as a separate entity. For robustness, we use a representation that includes all of the points in a selected region. The method works as follows:

1. Apply a global threshold.
2. Choose the highest salient point in saliency-space (\mathcal{Y}).
3. Find the K nearest neighbours (K is a pre-set constant).
4. Test the support of these using variance of the centre points.
5. Find distance, D , in \mathcal{R}^3 from salient regions already clustered.
6. Accept, if $D > scale_{mean}$ of the region and if sufficiently clustered (variance is less than pre-set threshold V_{th}).
7. Store as the mean scale and spatial location of K points.
8. Repeat from step 2 with next highest salient point.

The purpose of step 1 is to reduce computation time by removing the least salient features. This should be set quite low so as to keep all the features of interest and we have found that a 50% threshold (of the most salient feature value) works well. Both the V_{th} and K parameters affect the robustness of the resultant features. A greater value of K increases the number of salient points whose positions (in \mathcal{R}^3) must vary less than V_{th} to qualify as sufficiently clustered. Ideally, both of these should be related to the scale of the region under test. However, we have found that using fixed values was sufficient for our experiments. We used $K = 8$ and $V_{th} = 5$ for all of our experiments.

By testing centroid variance, the clustering algorithm favours isotropic regions. This reflects a similar property of the saliency algorithm as discussed in Section 4.3. A development of this algorithm could analyse the local autocorrelation or eigenstructure in order to perform grouping of the salient features. As stated earlier, this is the subject of ongoing research.

We have used this algorithm in all of the experiments presented in this paper. Figure 6 shows the results of the whole saliency algorithm, including clustering, applied to the DT and Vicky sequences. The new method captures salient features at various scales. For example, in the DT sequence both cars and pedestrians are represented at their appropriate local scales. In the original method, this was determined by the choice of the scale parameter.

6 Experimental results

In this section, we use the saliency method described above in a number of vision applications.

6.1 Scale and viewpoint robustness

In this section we demonstrate that the method is able to handle arbitrary changes in scale of the image and small changes in viewpoint of a 3D object. Under reasonable (but arbitrary) changes in magnification we would like the same salient locations to be selected along with their respective scales. This ‘fixing’ of the scale parameter should improve the performance of correspondence tasks, and also reduce the amount of data that needs to be stored to represent an object. Also, the method should be robust to small changes in the viewpoint of a 3D object. If this is the case then we can apply the method to 3D object representation by using multiple 2D views in a manner similar to that used by Schiele (1997).

In the example shown in figure 7, the superimposed circles represent the 10% most salient regions from two sizes of the Anacin image (from the Columbia image database (Nene et al., 1996)). The

larger image is the original, the smaller a 0.4 sub-sampled version. Independent Gaussian noise has been added to both images and the algorithm is run over the same range of scales (7-43 pixels diameter scales) in both images. Using a global threshold the method selected 40 salient regions from the first image and 29 from the second.

The image patches show the best matches between the two sets of salient regions, found by pixel correlation. It can be seen that the method is able to detect the correct matches as well as their respective scales - 13 of the icons selected from each set have close matches. The relative scale can be calculated from a simple consistency test on the relative scales of matched icons. This result demonstrates that it would be possible to represent the object using one set of salient icons and use this representation to recognise instances of the object at other arbitrary scales.

In the example shown in figure 8, the robustness of the method to small 3D rotations is demonstrated. Since the saliency method uses only local information, global transformations of the image have limited impact on the saliency. The experiment is carried out in a similar manner to the previous example except that two views of the object are used instead of two scales. Once again, a small amount of independent Gaussian noise is added to the two images prior to processing.

The method picked 29 salient regions for the original image and 28 for the 15° rotated version and found 18 matches.

6.2 Rotation and photometric invariance

In this section we demonstrate the method's invariance to planar rotation and changes in illumination.

The saliency algorithm calculates entropy of the local intensity PDF (in these experiments). Therefore, in the continuous case shifts in intensity make no difference to the entropy value. However, the histogram is only a discrete approximation to the true PDF and so shifts in intensity have a small effect on the local entropy (and hence the saliency value). This effect depends on the bin size of the histogram. Other PDF estimators, such as the Parzen window method, do not suffer from this problem but are computationally more expensive.

Scalings in intensity do affect the saliency value, but since the algorithm searches for maxima in entropy, the scales themselves should be quite robust. In terms of the hierarchy of salient regions found in a given image, uniform scalings in intensity applied to the whole image make little difference, apart from reducing the dynamic range between high and low saliency features (caused by the discretisation of intensities). Non-uniform scalings however, will cause the global ordering of the regions' saliencies to change. For example, it may occur that certain parts of an

image are illuminated better and hence higher variations in intensity are observed in that area. In an extreme case, probably such areas would be more perceptually salient. However, the saliency of a given region with respect to its local neighbourhood should be quite robust; that is, the local ordering of saliencies should be robust. Therefore a local post-processing clustering technique, such as described in Section 5, can overcome such problems.

In the case of rotation we expect the method to be invariant because the saliency algorithm uses circular local windows to sample the image. Discretisation may cause some problems at the smaller scales, however sub-pixel methods may be used to alleviate these.

Figure 9 shows the effect on the salient features of a 70% scaling (contrast reduction) of the image intensity values and a 45° clockwise rotation. The lower diagrams show the so-called Sparse Iconic representation used by Gilles. This shows the ‘icons’ matched by the algorithm in their image positions and scales.

6.3 Object Tracking and Recognition

In this section, our aim is to motivate the use of our saliency method in recognition and tracking tasks. In such tasks, two requirements of features and descriptions are that they should be *robust*, and *relevant*. The former is necessary to ensure stable descriptions under variations in viewing conditions; the latter, because it is desirable to relate descriptions to objects or parts thereof.

The purpose of this experiment is to demonstrate that features selected by our method are persistent in several instances of an object in a scene. The application is a simplified recognition and tracking scenario where the task is to identify close matches of a previously defined object in an image sequence, treating each frame independently. The persistence of features builds on the results of the previous sections and demonstrates robustness in a real scenario. By matching features with a model, we test their relevance with respect to the image objects they represent.

There was no attempt to develop a Kalman or Condensation (Blake and Isard, 1997) tracker. Such a tracker would further help the system in practice, but that is not the issue here. Treating each image independently represents a worst-case scenario that obviously could be improved by combining the ideas here with a tracker.

We used two sequences: the DT sequence from KOGS/IAKS Universität Karlsruhe, and the Vicky sequence. The models consisted of the clustered most salient regions and their scales found by running our algorithm on the (sub-)images shown in the top-left of figures 10 and 11. These are simply manually cropped from one frame in each sequence. In the Vicky experiment, two ‘takes’ of the sequence were available. We built the model from a single frame from one, and conducted

the experiment using the other.

The object is represented by a ‘constellation’ of salient regions. The algorithm was then applied to each frame of the sequence and instances on this constellation were identified. As in the previous experiments, normalised pixel correlation was used to find matches. This approach can be thought of as a powerful but least general descriptor. This was done in order to demonstrate the performance of the features independently of the properties of different descriptors. In practice, better descriptors, such as those with photometric and rotational invariance, should be used.

In order to show the scale invariance of the technique, the car model was built at the original resolution of the sequence and the recognition was carried out on a 0.7 spatially sub-sampled version. Edge preserving anisotropic diffusion was applied to each frame to reduce noise and interlace artifacts. For the Vicky experiment, anisotropic diffusion was not used, and the model generation and recognition were carried out at the same scale. In both experiments no assumptions were made about the scales between the model and test image, and no information was retained between frames.

Frames with superimposed results are shown in figures 10 and 11, with the most likely matches indicated by circles. We note the following. Firstly, that the method can consistently identify salient regions (as defined by our method) in an image sequence; similar features are consistently found even though each frame is treated independently. Secondly, that it can do this over arbitrary changes of scale and for small changes in view point of 3D objects. Note that this experiment involves a real camera sequence without pre-segmented objects. In this case, the model was built from one frame but was applicable to many frames in the sequence. Good approximations of the model positions are found in each frame.

Thirdly, the method could be used for recognition in quite complex scenes containing clutter and occlusion, without attempting to directly solve the segmentation problem. Common approaches for tracking and recognition in scenes such as this would normally apply some type of motion segmentation prior to recognition and these often require assumptions about global motion. We avoid this by using the saliency algorithm to select those regions and scales that are of interest, prior to recognition. Note that no assumption is made about global or object motion, so the method can be used to recover such motions. The technique vastly reduces the amount of information (positions and scales) that need to be considered at subsequent stages of processing. Finally, it illustrates the more general idea that local appearance descriptors can be useful for computer vision tasks as discussed in section 1.

It should be noted however, that the method only works well because the task was defined

around those objects that are classed as highly salient as defined by our method. Namely, compact patches with unpredictable grey-level pixel values. It could be argued that the cars are ‘the most interesting objects’ given no particular task other than to describe the scene in a general sense; of course the method could also work in space and time (and scale) in which case the motion of the cars would further increase their saliency. However, the task could have been to track some of the less salient parts, for example the pedestrians. There are two important points relevant to this issue. The first is that the method does not itself threshold out the less salient regions, but generates a hierarchy of salient regions. In this experiment we have used a global threshold to remove the low saliency features, but we could have considered features as representing local regions and scales in an image. For example, although a particular feature may not have a globally high saliency, locally it might be the most interesting feature in that part of the image and at that scale. Our simple clustering algorithm does attempt to do this but in a very crude way. The second point is that of the prior model used for the saliency definition. We have used grey-level distribution, but different feature maps could be used. This is an important issue which will be discussed in more detail in section 7.

A number of false positives are detected. This is due to the simple object model that has been used. Note that the method has not used any scale consistency nor local configuration information for the model; both of these would eliminate a large number of the false positives. For example, it can be assumed that the salient features comprising the model, scale consistently (with respect to one another), in given instances of the object in the test sequence. This would be a very general and effective technique. That is, scale factors between the features in the model and those matched in the scene should be consistent. Furthermore, it can be assumed that smooth changes in camera position or object depth would result in smooth changes in selected scale. We could use this information in conjunction with a tracker to further improve the performance of the basic technique.

We have deliberately omitted such enhancements at the higher layers of processing to emphasise the performance of the technique (since it is a low-level early vision algorithm). The fact that a crude object model and a simple pixel matching method has been used, yet has achieved good results demonstrates that the quality of the information computed by our technique is very good. We accept that there are many methods that could be used to improve these results and in fact probably many alternative techniques that could be used to achieve better results with this and other similar sequences. The experiments here are designed to justify the arguments made in this paper.

7 Discussion - What is the prior model ?

The concepts that have been used in our saliency technique imply some kind of prior; in other words there is a benchmark that local complexity is measured against. In this section we discuss what this is and the resulting implications on the appropriate selection of descriptors for our saliency measure.

Consider an example of measuring the predictability of a local image region's intensity values. First, we compute the local histogram of grey-values; this approximates the local PDF of grey-values. If the histogram is highly peaked around a specific intensity range then this (by definition) means that, within this region it is highly likely that pixel values within that particular intensity range can be found. If the PDF is spread out, it means that many intensity values are equally likely. Entropy simply summarises the degree to which a PDF is peaked or spread out. We label those areas with a flat PDF (i.e. high entropy) as salient, and can use these in further processing.

There is an apparent paradox here: A sharply peaked PDF is generally considered highly informative, yet in our method this is labelled with low saliency. In Shannon Information theory, information is often considered to be opposite to entropy.

Placing the sampling procedure in a Bayes framework provides a useful insight:

$$p(A | B, s) = \frac{p(B | A, s)p(A, s)}{p(B, s)} \quad (7)$$

where $p(B | A)$ is the measurement, $p(A)$ is the prior and $p(A | B)$ is the posterior PDF that is then used to calculate the entropy; all of these are taken with respect to the local region at scale s . In the example above, nothing is assumed about the prior distribution of intensity values within the local region and so $p(A)$ is uniform. If, after measurement, the posterior PDF is very sharply peaked, then the measurement must have been very informative. Given this, the region can be described well using very few parameters in the descriptor (probably just an average grey-value will do). This means that the representation of the local region as a few intensity values is a good way of representing that region.

A flat posterior PDF means that nothing new has been learnt from the measurement process (except that the region does not have very predictable intensity values). In this case the local region is not very well captured by an intensity representation and hence a more powerful descriptor is needed to accurately describe the region. In other words, the local PDF of a descriptor measures how well that descriptor captures the local signal behaviour. If it captures it well, then this is classed as non-salient and if not then this is salient.

It follows that the technique can be considered to model the non-salient parts of a signal rather than the salient parts. Saliency is defined as those parts of the signal that cannot be represented well by our prior model. Therefore the entropy of a descriptor tells us how well that descriptor captures the local region's data. This is opposite to the way in which most feature extraction and visual saliency techniques work, but is actually rather intuitive. Those parts of an image that are most informative are those that do not get modeled well (or predicted) by our prior assumptions or put another way: if we can model them then they're probably not all that interesting. We assume that the prior model captures the common or widespread behaviour of the signal. In the examples used in this paper the non-saliency model is a piecewise flat local image patch and the assumption here is that piecewise flat parts are very common and not very interesting.

7.1 Choosing Descriptors for Saliency

In this paper all the results and examples that have been presented have used the local intensity as the descriptor for saliency. Given the above re-interpretation, the technique can be stated as : Given a descriptor with one (or more) free parameters, describe the local region's signal; its saliency is inversely related to how good (or compact) this description is. Therefore in designing appropriate descriptors for saliency all the parameters of what is non-salient should be included in the descriptor. For example, for selection of salient regions in fingerprint images, an edge detector at multiple orientations and scales can be used. The descriptor, in this case, is a region containing a line with a variable scale and orientation. This would model low saliency as a single line at some orientation at a single thickness. In this case salient regions could be where there are multiple lines joining together, as occurs at bifurcations. Figure 12 shows an example of this. We have used a Gaussian derivative at a particular scale and assigned a single dominant orientation to each pixel location. Our multiscale saliency algorithm has then been applied to this feature map and the most salient parts shown with superimposed circles.

7.2 Saliency and description

In the Introduction, it was argued that the use of saliency methods should enable better and more compact image descriptions to be obtained. This should improve the performance of correspondence and matching tasks. In this section we discuss the link between saliency and description tasks within our framework.

Approaches in the literature have tended to select salient features separately from their subsequent description. Gilles (Gilles, 1998) does not suggest any link between the two processes and

uses the image patches directly. Schmid and Mohr (1997) use the Local Jet at multiple scales to describe the image near Interest points. However there is no justification of why these descriptors are good for the particular choice of salient feature.

Earlier it was discussed that our saliency method could be considered to model the low-saliency parts of the image. Entropy of a local descriptor measures the degree to which that descriptor captures local signal behaviour and these are chosen to represent efficiently (from an information theory point of view) those parts of an image which are non-salient. The regions which are classed as highly salient are those which are not well represented by that descriptor and need different (more powerful) descriptors. The entropy method can be used to test how well a descriptor performs. We may generalise the approach. Rather than applying one saliency measure and then describing the salient parts, we propose that a hierarchy of increasingly powerful descriptors be applied and tested. At each level, we can extract the non-salient features which can be described well by the descriptors at that level. The salient parts can then be tested using more powerful descriptors until all the image has been sufficiently described.

In Gilles' original work, salient local image patches were described as vectors of pixel values for the subsequent matching task. This can be thought of as a very powerful descriptor (high dimensional). We have used the same approach in our experiments. Different descriptors may be used, which may have advantages such as photometric or rotational invariance.

7.3 Spectral and Wavelet entropy

In this section we discuss the relationship of our method to two related signal complexity measures, Spectral entropy (Zheng et al., 1996) and Wavelet entropy (Starck and Murtagh, 1999). A corollary of this relationship is that there are also strong links to image compression and Wavelet packet best basis selection techniques (Coifman and Wickerhauser, 1992).

Spectral entropy is used by the Neural Network community to measure pattern complexity. It is calculated directly from the Fourier coefficients of transformed signal. Wavelet entropy has been proposed by Murtagh as a technique for image feature extraction and content description (Starck and Murtagh, 1999). It also calculates entropy directly from the (Wavelet) basis coefficients, but introduces a noise model which improves robustness. They are both multiscale in the sense that they consider different scales in calculation of the complexity of the signal.

Both these methods can be considered in the context of our saliency technique as different local descriptors of non-saliency. For example, in the case of Spectral entropy, if we were to classify as salient those regions with many coefficients with similar magnitudes, then the prior model we have

used for non-saliency is that of a region containing a single frequency (band). The descriptors for non-saliency form a much richer set in this case than in the intensity distribution case. Wavelet entropy can be analysed in a similar manner. Furthermore, there may be benefits of using Spectral or Wavelet entropy over intensity distribution entropy; one example is the noise model included in the method used in (Starck and Murtagh, 1999).

Compression techniques commonly take advantage of the decorrelation properties of transforms such as the Discrete Cosine Transform or the Wavelet Transform, to achieve compression. The idea is that the signal is transformed into a set of decorrelated or orthogonal basis vectors which, after appropriate quantisation, can represent the signal in a more efficient manner. The method works most efficiently if the signals found in the source can be represented well by a small number of the basis vectors - that is the basis set can synthesize the source signals with only a few parameters. Our saliency method with a local descriptor set made from the local Fourier or Wavelet coefficients, bears a strong resemblance to signal compression techniques. Non-salient parts of the image are those that contain significant redundancy and can be compressed quite easily.

Entropy is also widely used in the selection of best basis in Wavelet packet methods (Coifman and Wickerhauser, 1992). Here the basis with the minimum local entropy is classified as the best; that is, the one with the fewest negligible coefficients. Once again, there is a strong link with our approach to saliency and description.

7.4 Saliency and segmentation

The task in segmentation is to group image pixels such that the groups satisfy some definition of homogeneity. For example this may be that the regions are piecewise continuous in intensity, of similar texture, or have similar motion vectors. In the entropy of intensity approach to saliency, the task is to find groups of pixels which are different from each other (but close spatially) according to the assumed definition of non-saliency. In the intensity distribution local descriptor that has been used for the majority of the experiments in this paper, groups containing many different pixel values in equal proportion are considered salient. In this way, the method can be viewed as the opposite to the classic segmentation problem. The salient regions can be considered as the outliers of the homogeneous regions after segmentation. In fact Gilles did suggest that his method could be used to select seed points for a segmentation algorithm.

8 Conclusion

In this paper we have presented a discussion of three separate but closely related issues common in many computer vision problems: saliency, scale, and image description.

In many computer vision tasks we would like to extract ‘meaningful’ and general descriptors of image content. Descriptors have to be appropriate to the task at hand to be useful, but early vision in humans is believed to operate with little contextual information. From the popular pre-attentive and attentive models of early vision, and from several recent results it is known that local features can be ‘good enough’ to solve many computer vision tasks. We have discussed the idea of visual saliency which suggests that certain regions of the image are better than others at describing content and we have suggested that this approach can solve some of the problems associated with purely local methods.

Motivated by the promising results obtained by Gilles, we have investigated his local complexity approach to visual saliency applied to a wide range of image source material including image sequences. Our experiments showed that local scale selection was necessary but furthermore that the method had to be extended to consider saliency across scale as well as spatial dimensions. We have introduced a novel saliency method that builds on Gilles ideas but automatically selects appropriate scales for analysis and can compare the scale-space behaviour of image features. We then presented results showing the performance of the technique, in particular its invariance to scale changes in the image and view point changes in 3D objects. We then applied the technique to an object recognition and tracking task in an image sequence. Using a crude object model and pixel correlation matching, the technique was successful in identifying matches of the model in an image sequence consisting of a complex scene. In these examples, we used a minimal set of prior assumptions in order to highlight the performance of the basic technique. Further enhancements can be made to the technique by using, for example, a Condensation or Kalman tracker or by making basic assumptions about the consistency of scales between model and image, or smoothness of changes in position and scale between frames in an image sequence. The use of such assumptions is the subject of further investigation and results will be reported in a future paper. We are also investigating the application of the technique to large database object recognition problems and will report on these results in a future paper.

In the last section we investigated the links between saliency and image description. In many approaches to saliency these two issues have been separately handled. Features that have been selected using a saliency algorithm are then described by using an arbitrary description method (and in some cases arbitrary scales). On the contrary we argue that the two tasks should be

considered as parts of the same problem. Having analysed the prior model for saliency that we have used in the experiments, we conclude that the method measures how well a given local descriptor captures local signal behaviour. Low saliency regions are those that can be modeled very well by the chosen local descriptor (in information theory this means ‘in few bits’; in signal processing this can mean ‘good signal to noise ratio’). In the example of local intensity distribution low saliency regions are those that are piecewise flat. In other words the prior model should be designed such that the non-salient features are well described; the saliency descriptor models the background rather than foreground. This approach is quite distinct from conventional approaches to saliency. We presented an example where we wish to find the salient parts in a fingerprint image. The model of non-saliency in this case is a single direction edge at a particular scale. Salient parts are those with many directions and scales. The method can in this way be generalised for any prior model. Subsequent description of that image feature should be done by a more discriminating descriptor than the one used for saliency.

Having made this observation, a number of other relations become obvious: Spectral/Wavelet entropy are simply the same method but with different local descriptors; Segmentation is the opposite to saliency (as we have defined it); strong connections exist to compression coding where redundancy (low-saliency) is taken advantage of to achieve compression.

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References

- L. Alvarez, P. Lions, and J. Morel. Image selective smoothing and edge detection by nonlinear diffusion. II. *SIAM Journal on Numerical Analysis*, 29(3):845–866, June 1992.
- F. Bergholm. Edge focusing. In *Proc. Int. Conf. on Pattern Recognition*, pages 597–600, October 1986. Paris, France.
- A. Blake and M. Isard. The CONDENSATION algorithm — conditional density propagation and applications to visual tracking. In Michael C. Mozer, Michael I. Jordan, and Thomas Petsche, editors, *Advances in Neural Information Processing Systems*, volume 9, page 361. MIT Press: Cambridge, MA., 1997.
- P.J. Burt and E.H. Adelson. The Laplacian pyramid as a compact image code. *IEEE Trans. Communication*, 31(4):532–540, April 1983.
- O. Chomat, V.C. deVerdiere, D. Hall, and J.L. Crowley. Local scale selection for gaussian based description techniques. In *Proc. European Conf. Computer Vision*, pages 117–133, 2000.
- R. Coifman and M. Wickerhauser. Entropy-based algorithms for best basis selection. *IEEE Trans. on Information Theory*, 38(2):713–718, 1992.
- R. Deriche and T. Giraudon. A computational approach for corner and vertex detection. *International Journal of Computer Vision.*, 10(2):101–124, 1993.
- Y. Dufournaud, C. Schmid, and R. Horaud. Matching images with different resolutions. In *Proc. Int. Conf. on Computer Vision and Pattern Recognition*, pages I:612–618, 2000.
- S. Gilles. *Robust Description and Matching of Images*. PhD thesis, University of Oxford, 1998.
- C. Harris and M. Stephens. A combined corner and edge detector. In *Proc. 4th Alvey Vision Conf*, pages 189–192, August 1988. Manchester.
- M. Jägersand. Saliency maps and attention selection in scale and spatial coordinates: An information theoretic approach. In *Proc. Int. Conf. on Computer Vision*, pages 195–202, 1995. MIT Cambridge, MA.
- B. Julesz. *Dialogues on Perception*. MIT Press, 1995.
- J.J. Koenderink. The structure of images. *Biological Cybernetics*, 50:363–370, 1984.

- J.J. Koenderink and A.J. van Doorn. Representation of local geometry in the visual system. *Biological Cybernetics*, 63:291–297, 1987.
- Y.G. Leclerc. Constructing simple stable descriptions for image partitioning. *Int. Journal of Computer Vision.*, 3:73–102, 1989.
- T. Lindeberg. On scale selection for differential operators. In *Proc. 8th Scandinavian Conf. on Image Analysis*, pages 857–866, Tromso, Norway, May 1993.
- T. Lindeberg. Junction detection with automatic selection of detection scales and localization scales. In *Proc. Int. Conf. on Image Processing*, pages 924–928, November 1994.
- T. Lindeberg and B.M. ter Haar Romeny. *Linear Scale-Space: I. Basic Theory, II. Early Visual Operations. In Geometry-Driven Diffusion, B.M. ter Haar Romeny (Ed.)*. Kluwer Academic Publishers, Dordrecht, The Netherlands., 1994.
- S. Mallat. *A Wavelet Tour of Signal Processing*. Academic Press, San Diego, 1998.
- D. Marr. *Vision: a Computational Investigation into the Human Representation and Processing of Visual Information*. W. H. Freeman, San Francisco, 1982.
- D. Marr and E. Hildreth. Theory of edge detection. *Proceedings Royal Society of London Bulletin*, 204:301–328, 1979.
- R. Milanese. *Detecting Salient Regions in an Image: From Biological Evidence to Computer Implementation*. PhD thesis, University of Geneva, 1993.
- F. Mokhtarian and R. Suomela. Robust image corner detection through curvature scale space. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 20(12), 1998.
- U. Neisser. Visual search. *Scientific American*, 210(6):94–102, June 1964.
- S. Nene, S. Nayar, and H. Murase. Columbia image object library. Technical report, Department of Computer Science, Columbia University, 1996.
- P. Perona and J. Malik. Scale space and edge detection using anisotropic diffusion. In *Proc. Int. Conf. on Computer Vision and Pattern Recognition*, pages 16–22, 1988.
- B. Schiele. *Object Recognition Using Multidimensional Receptive Field Histograms*. PhD thesis, I.N.P. de Grenoble, 1997.

- C. Schmid and R. Mohr. Local greyvalue invariants for image retrieval. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 19(5):530–535, 1997.
- C. Schmid, R. Mohr, and C. Bauckhage. Comparing and evaluating interest points. In *Proc. Int. Conf. on Computer Vision*, pages 230–235, 1998.
- A. Sha’ashua and S. Ullman. Structural saliency: the detection of globally salient structures using a locally connected network. In *Proc. Int. Conf. on Computer Vision*, pages 321–327, 1988. Tampa, FL.
- J. Starck and F. Murtagh. Multiscale entropy filtering. *EURASIP Signal Processing*, pages 147–165, 1999.
- M.J. Swain and D.H. Ballard. Colour indexing. *International Journal of Computer Vision*, 7(1): 11–32, 1995.
- B.M. ter Haar Romeny. *Introduction to Scale-Space Theory: Multiscale Geometric Image Analysis*. PhD thesis, Utrecht University, 1996.
- A. Treisman. Preattentive processing in vision. *Computer Vision, Graphics, and Image Processing*, 31(2):156–177, 1985.
- K.N. Walker, T.F. Cootes, and C.J. Taylor. Locating salient facial features using image invariants. In *Int. Conf. on Automatic Face and Gesture Recognition*, 1998a. Nara, Japan.
- K.N. Walker, T.F. Cootes, and C.J. Taylor. Locating salient object features. In *Proc. British Machine Vision Conference*, pages 557–566, 1998b. Southampton, UK.
- J. Weickert. A review of nonlinear diffusion filtering. *Lecture Notes in Computer Science*, 1252: 3–28, 1997.
- A. Winter, H. Maitre, N. Cambou, and E. Legrand. Entropy and multiscale analysis : an original feature extraction algorithm for aerial and satellite images. In *Proc. Int. Conf. on Acoustics, Speech, and Signal Processing*. IEEE, April 1997.
- A. Witkin. Scale-space filtering. In *Proc. Int. Joint Conf. on Artificial Intelligence*. Karlsruhe, Germany, 1983.
- B.Y. Zheng, W. Qian, and L.P. Clarke. Digital mammography - mixed feature neural network with spectral entropy decision for detection of microcalcifications. *IEEE Trans. on Medical Imaging*, 15(5):589–597, 1996.

S.C. Zhu and A. Yuille. Region competition: Unifying snakes, region growing, and bayes/mdl for multiband image segmentation. *IEEE Pattern Analysis and Machine Intelligence*, 18(9):884–900, September 1996.

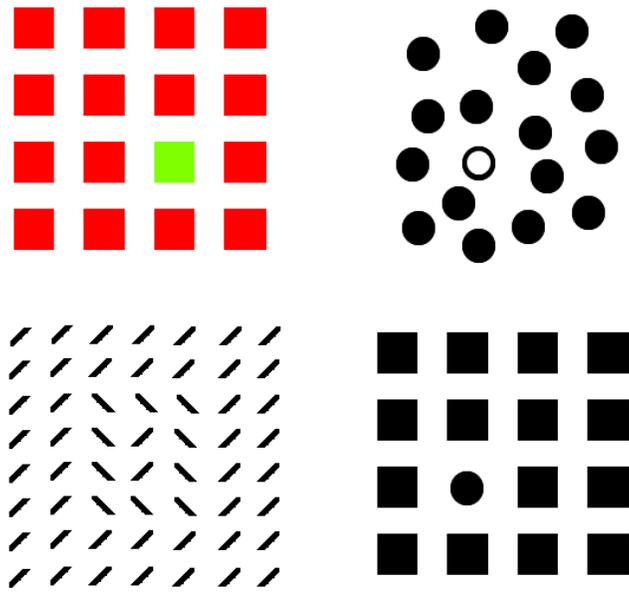


Figure 1: Examples of Visual Saliency.

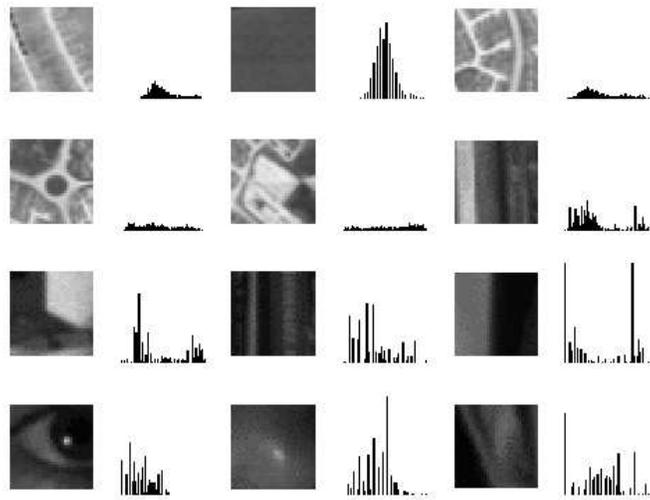


Figure 2: The local histograms of intensity. Uniform images tend to have peaked histograms indicating a low complexity (or high predictability). Neighbourhoods with structures have flatter distributions, that is, a higher complexity. Reproduced with permission from (Gilles, 1998).

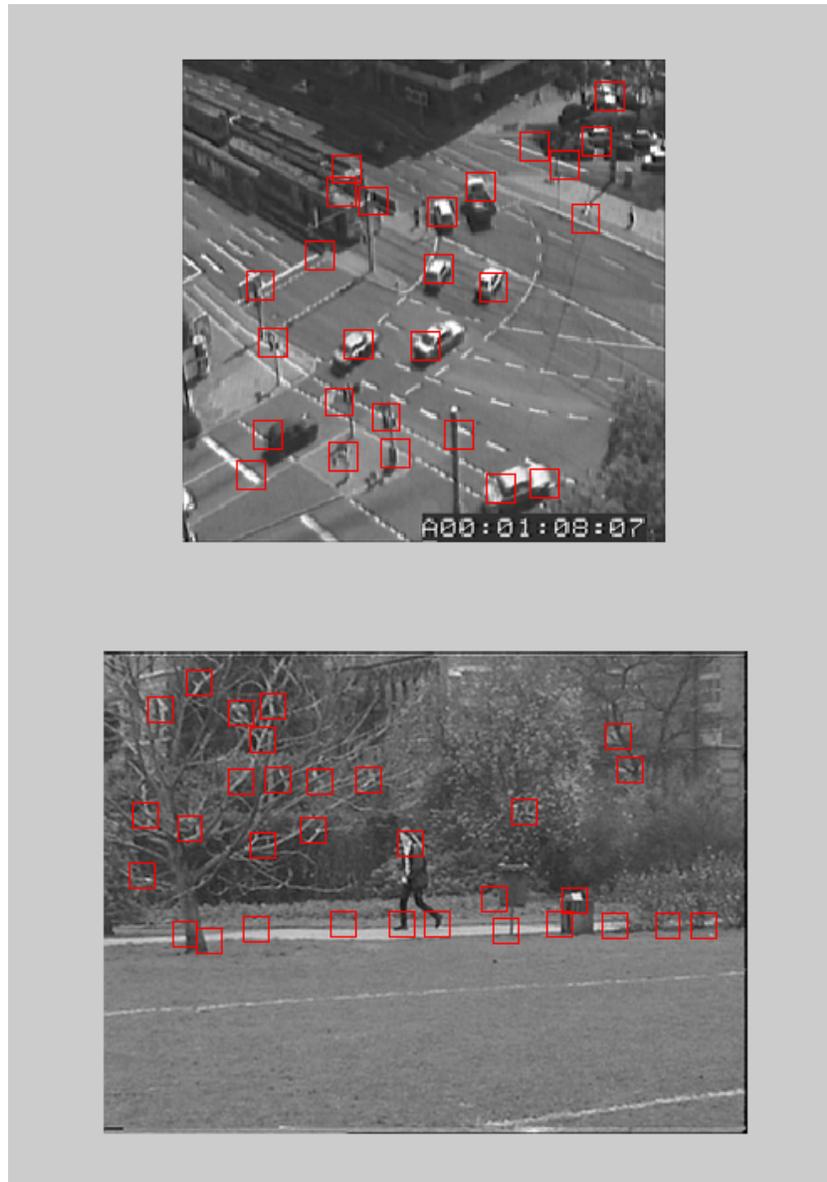


Figure 3: Example frames from the application of the original Gilles algorithm to the DT (top) and Vicky (bottom) sequences.

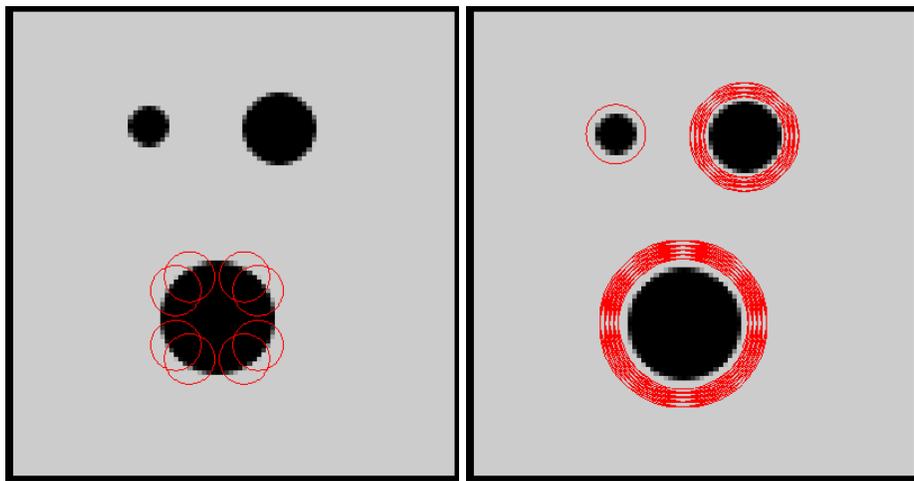


Figure 4: Most salient parts: selected using peaks in entropy versus scale (left); selected using peaks in entropy versus scale weighted by sum of absolute difference at peak (right).

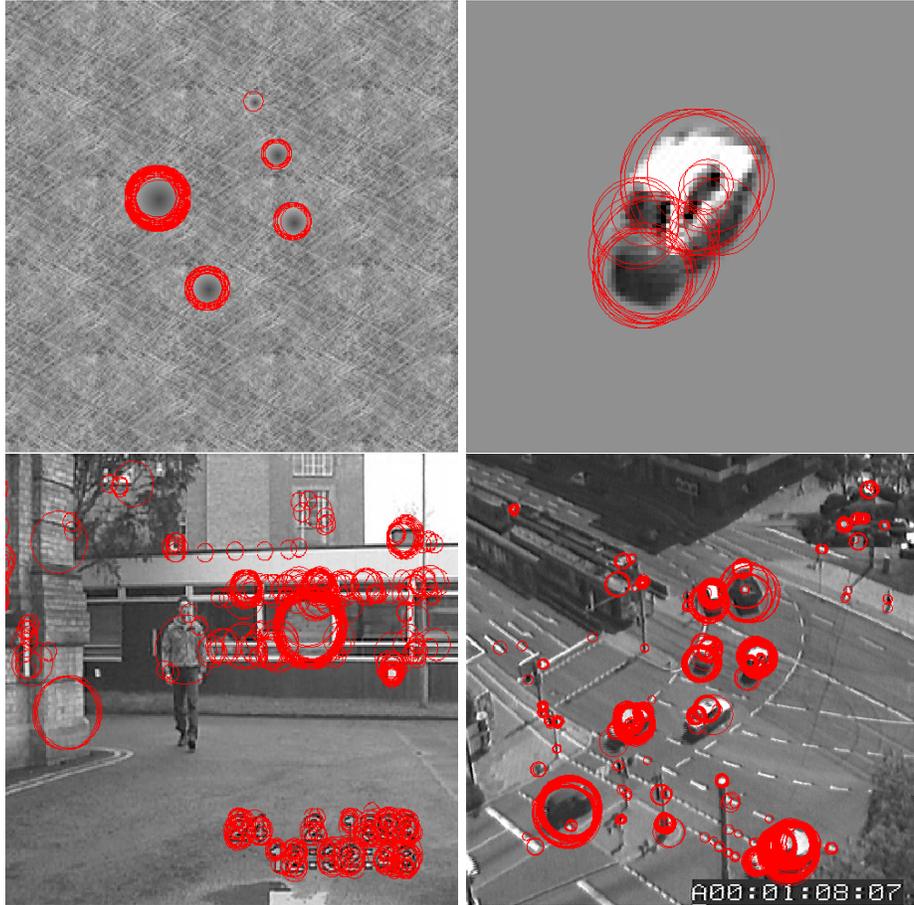


Figure 5: The new algorithm: Picking the most salient points and their scales. A global threshold is used.



Figure 6: Example frames from the application of the new algorithm to the DT (top) and Vicky (bottom) sequences. Salient regions selected using the clustering algorithm.

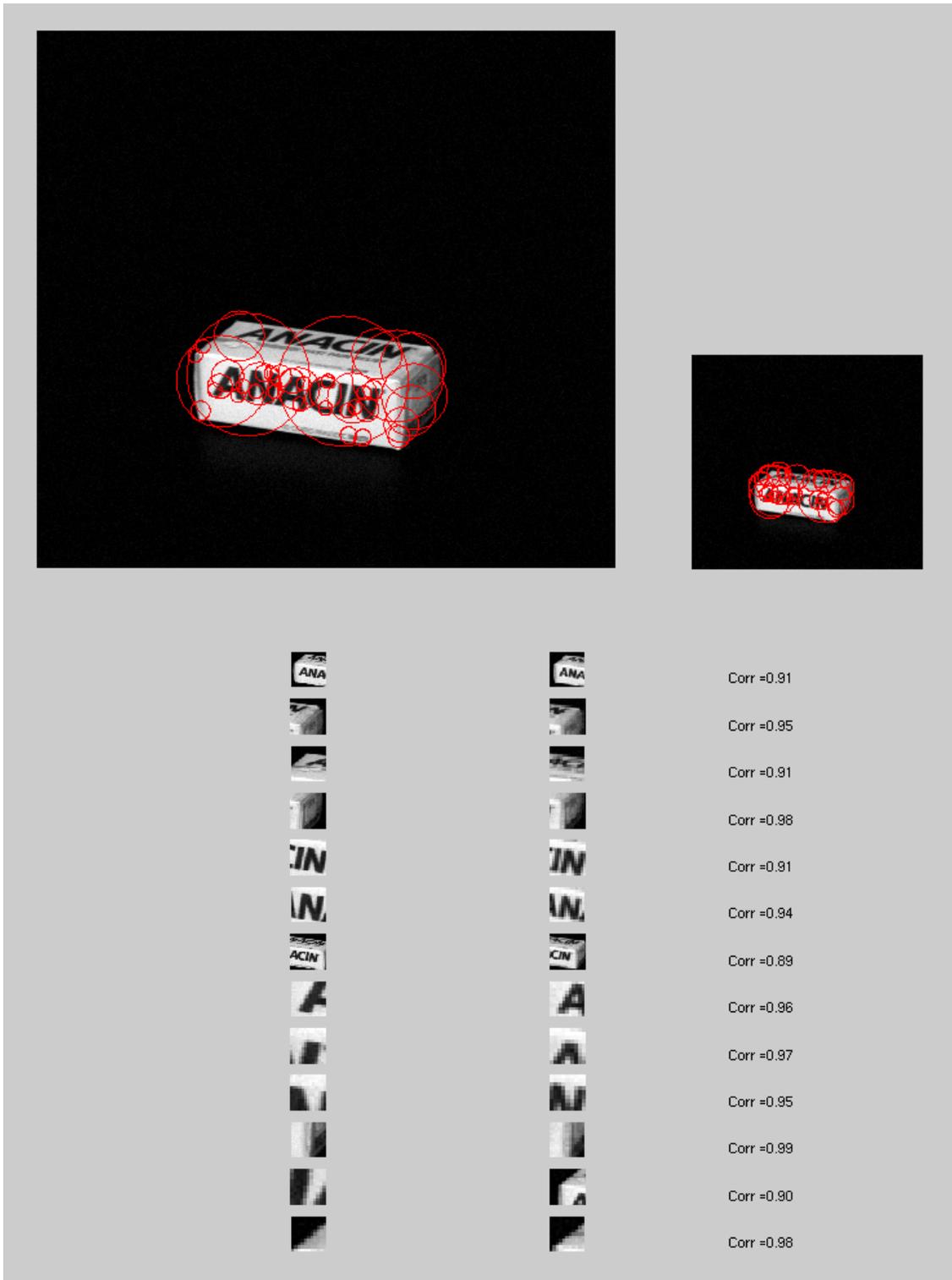


Figure 7: Matching salient icons between the original sized image and a 0.4 sub-sampled version in noise.

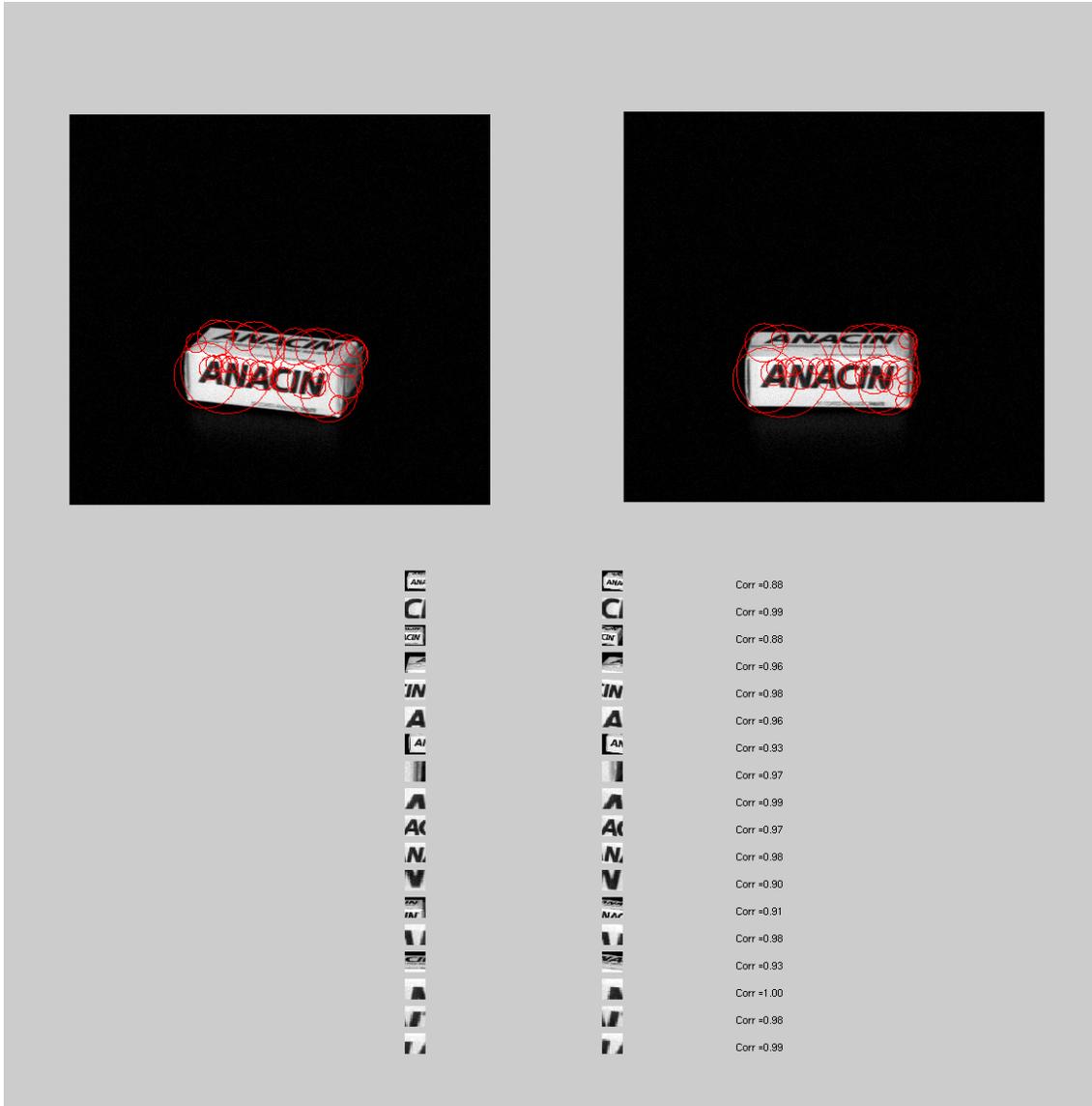


Figure 8: Matching salient icons between 0° and 15° viewpoint change (in noise).

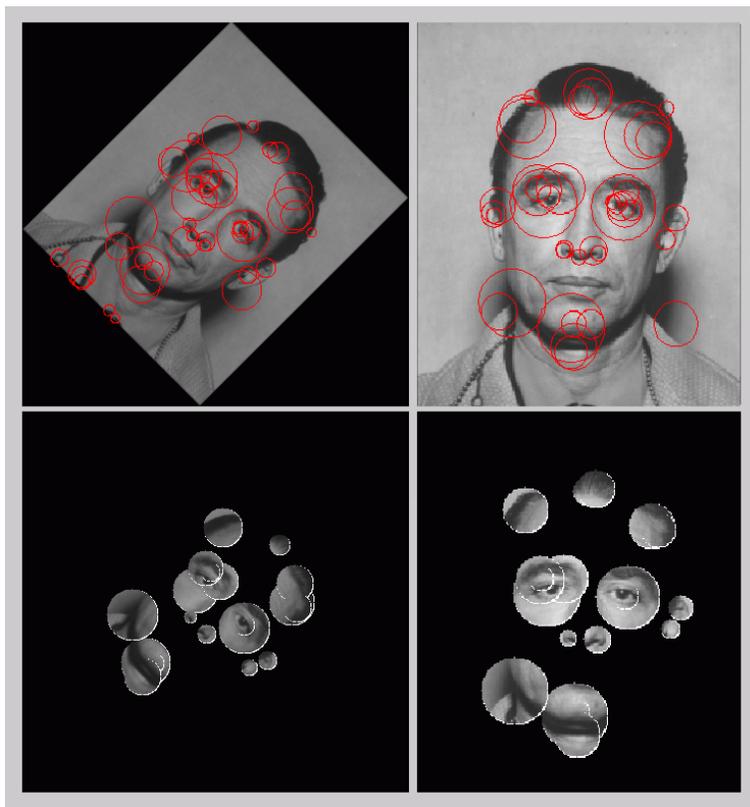


Figure 9: Robustness to rotation (45°) and illumination change (70% scaling). The upper images show the salient regions found in each image, the lower row the Gilles Sparse Iconic Representation of matches. Image from NIST Special Database 18, Mugshot Identification Database.



Figure 10: Results from the recognition experiment on the DT sequence. The top-left shows the (enlarged) image of the car from which the object model was built. The superimposed circles show the features in each frame which match with the object model.



Figure 11: Results from the recognition experiment on the Vicky sequence. The model was generated from the top-left image (taken from vicky1) cropped to the rectangle. The superimposed circles show the features in each frame (of vicky2) which match with the object model.

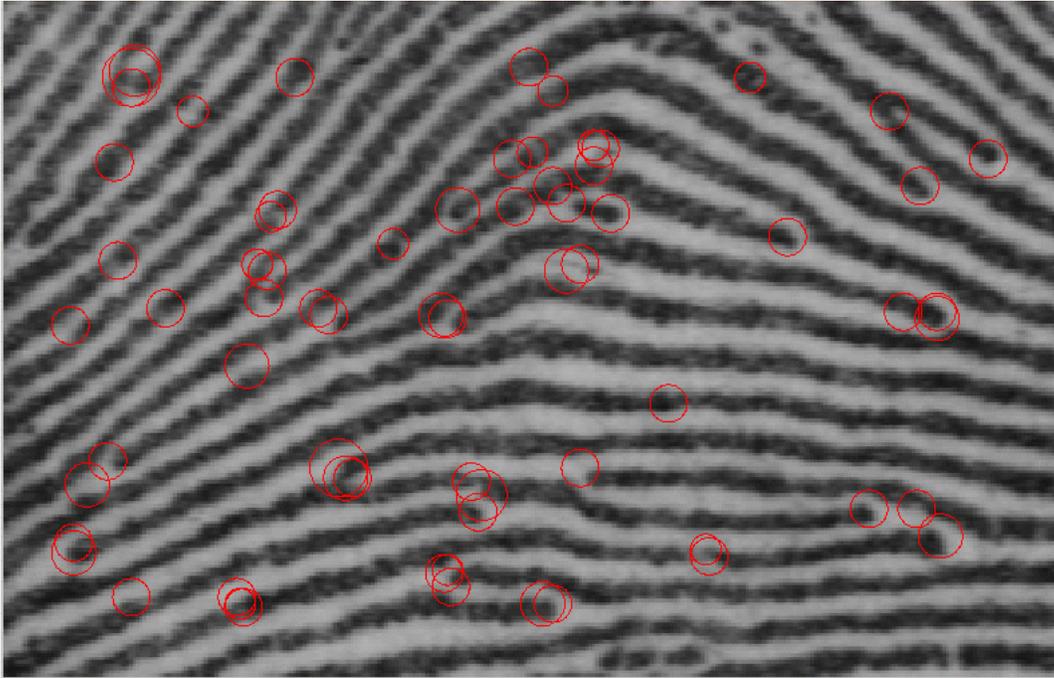


Figure 12: Using dominant edge directions at a certain scale as the non-salient descriptor on a fingerprint image.

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Footnotes

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(1) We do not advocate the use of one particular scale space representation in our work. Rather we are interested in scale selection and the extension of saliency to operate over scale. We have used a circular top-hat sampling kernel to generate our scale space for reasons of simplicity, rotational invariance (in the image plane) and because it does not alter the statistical properties of the local descriptor.

(2) Copyright (c) 1998 by H.H. Nagel. Institut für Algorithmen und Kognitive Systeme. Fakultät für Informatik. Universität Karlsruhe (TH). Postfach 6980.D - 76128 Karlsruhe, Germany.

(3) Histograms are not confined to intensity; they may be any local attribute such as colour or edge strength, direction or phase.

(4) Note, these operators do not exclusively select features that are perceived to be the corners of objects; rather, they compute sets of zero measure typified by their peaked autocorrelation.

(5) Gilles was primarily interested in the matching of aerial images.

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