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(71) Applicant *(for all designated States except US)*: CORNELL RESEARCH FOUNDATION, INC. [US/US]; Suite 105, 20 Thornwood Drive, Ithaca, NY 14850 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: BODENSCHATZ, Eberhard [DE/US]; Cornell Research Foundation, Inc., Suite 105, 20 Thornwood Drive, Ithaca, NY 14850 (US). EGOLF, David, A. [US/US]; Cornell Research Foundation, Inc., Suite 105, 20 Thornwood Drive, Ithaca, NY 14850 (US). MELNIKOV, Ilarion, V. [US/US]; Cornell Research Foundation, Inc., Suite 105, 20 Thornwood Drive, Ithaca, NY 14850 (US).

(74) Agents: COHEN, Jerry et al.; Perkins, Smith & Cohen, LLP, One Beacon Street, Boston, MA 02108 (US).

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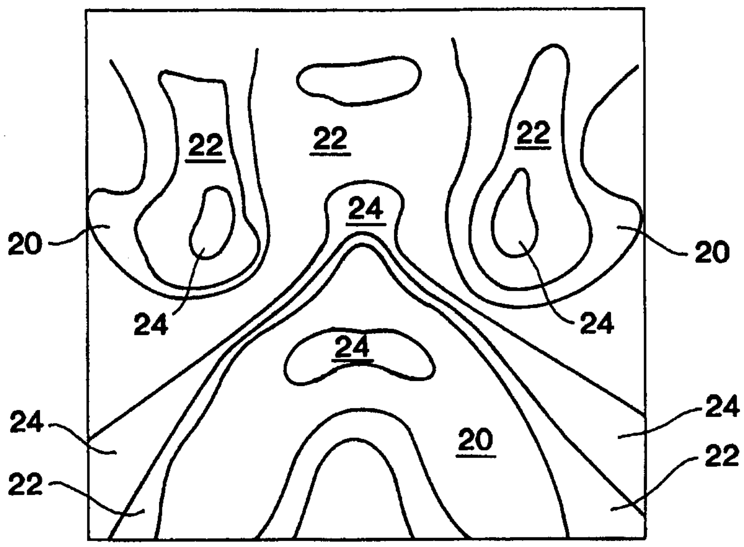
(54) Title: A FAST METHOD AND SYSTEM FOR DETERMINING LOCAL PROPERTIES OF STRIPED PATTERNS



(57) Abstract

The present invention describes a system and method for determining local pattern properties such as wavenumber (20, 24), orientation, curvature, defect types, and their locations in striped patterns. Such patterns are found in a wide variety of technical disciplines. The striped pattern is locally approximated by a sinusoid from which a wavedirector field can be formed by differentiation. The orientation and curvature can be determined, and defects can be found and classified. These properties can be measured over time to provide useful information about the temporal characteristics of various physical phenomena that produce locally striped patterns. The measured local properties can be smoothed by various techniques, preferably using Gaussian blur. It has been found that the present invention provides a means for generating such properties more quickly and with greater accuracy and precision than prior art approaches.

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A FAST METHOD AND SYSTEM FOR DETERMINING LOCAL PROPERTIES OF STRIPED PATTERNS

STATEMENT OF GOVERNMENT INTEREST

This invention was made with U.S. Government support from the National Science Foundation. The U.S. Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

This invention relates generally to determining properties of patterns, and, more particularly to fast determination of properties of striped patterns.

From the striped coats of zebras, to fingerprints, to the ripples in windblown sand, the natural world abounds with locally banded patterns. In technological applications one is often interested in slowly varying periodic signals. For example, striped interference patterns are used to measure height or refractive variations. Fast, quantitative methods are needed to characterize the static features and the dynamics of these complicated striped patterns. The characterization needed includes: wavenumber as a function of position in one or two dimension patterns, and orientation and curvature as functions of position in two dimensional striped patterns. Moreover, it is important to locate and identify defects in the pattern (e.g. disclinations dislocations, and grain boundaries).

Prior researchers have used power spectra and statistics derived therefrom, such as the spectral pattern entropy to analyze striped patterns. However, these are global quantities, and they can only serve as approximations of local pattern properties.

Several researchers have explored the usefulness of local pattern properties to describe locally striped patterns. Heutmaker and Gollub, in a paper, "Wave-vector Field of Convective Flow Patterns," *Phys. Rev. A,* 35:242-260 (1987), determined the wavevector field and statistics such as "roll bending" and "roll obliqueness" patterns in a circular Rayleigh-Benard convection cell to understand the stability of convective patterns. More recently, Hu, et al., in a paper, "Convection for Prandtl Number Near 1: Dynamics of Textured patterns," *Phys. Rev. E,* 51:3263 (1995), computed local wavenumbers and curvatures in experimental pictures of locally striped patterns and proposed order parameters to describe transitions in spatiotemporal chaos in Rayleigh-Bernard convection. In a numerical study of a model of Rayleigh-Benard convection rotated about a vertical axis, Cross, et al., in a paper, "Chaotic Dynamics: A numerical Investigation,"*Chaos,* 4:607 (1994), computed the local orientation of rolls to characterize domain structure. Ouyang and Swinney, in a paper, "Transition to Chemical Turbulence,"*Chaos,* 1(4):411-420 (1991), also used the local orientation to analyze patterns in a chemical reaction-diffusion system. Gunaratne et al., in a paper, "An Invariant Measure of Disorder in Patterns," *Phys. Rev. Lett,* (1995), have suggested an invariant measure of the disorder of locally striped patterns, and they have demonstrated its use on reaction-diffusion patterns. Newell et al., in a paper, "Defects are Weak and Self-dual Solutions of the Cross-Newell Phase Diffusion Equation for Natural Patterns," *Physica D,* 97:185 (1996), have begun to use local wavenumbers to study the behavior of phase-diffusion equations in the presence of defects.

These previous studies clearly demonstrate the utility of local pattern properties. However, these earlier studies were limited by the large amount of time it required to process each snapshot of complicated time-dependent patterns.

It is an object of the present invention to provide a real time method for calculating local properties of locally striped patterns in one or two dimensions.

It is still another object of the present invention to provide new tools for research on striped patterns.

It is still a further object of the present invention to provide local wavenumbers, local orientation, local curvature, locations and types of pattern defects, and statistical data of these local properties.

SUMMARY OF THE INVENTION

The objects set forth above as well as further and other objects and advantages of the present invention are achieved by the embodiments of the invention described herein below.

In a striped pattern the field may be approximated locally by a sinusoidal function. From this function a local wavedirector is defined as the gradient of the argument of the sinusoidal function. In a one dimensional system the magnitude i.e. the wavenumber may be determined. In a two dimensional system the magnitudes and the relative signs of the components of the wavedirector in x and y directions may be calculated. The wavedirector is so termed since the direction of this vector is equivalent to the same vector with negated x and y component values and its magnitude gives the local periodicity, i.e. the local stripe spacing.

In a locally striped area of a pattern (everywhere but at defects) the calculations of the component values of wavevectors in those areas provide the local wavenumber (number of waves per unit length), the local curvature, and the local orientation as functions of x and y. Moreover, the time dependence of these properties can be determined by analyzing a time sequence of images.

Defects in the locally striped pattern can be determined from the wavedirector. Disclinations can be found by calculating the number of full rotations of the director around each point (x,y). Grain boundaries can be identified as jumps of the orientation around a point of interest. The location of dislocations, i.e. the point where a stripe ends can be found by going on a closed loop around a point of interest. The calculation of $W = \frac{1}{2\pi}\oint \overleftrightarrow{k} \cdot \vec{dl}$ gives the winding number W. If $W = \pm 1$, there is a "+1" or "-1" dislocation at the point of interest, otherwise there is none. ($\vec{k}$ is the wavedirector and $\vec{dl}$ describes the path taken). If the closed loop is around a larger area the integral gives the excess number of "+" OR "-" dislocations for that area. As $\vec{k}$ is a director, in performing the above path integral. Care must be taken to keep $\vec{k}\vec{dl}$ continuous. This is accomplished by using the negated components of "out of line" $\overleftrightarrow{k}(x)$ values. This problem also needs tp be considered when calculating the curvature. Defects (grain boundaries disclinations and dislocations) are characteristics of a pattern. Other characteristics in such patterns that may be determined are properties such as the correlation functions of orientation and curvature. From these characteristics statistics (in space and time) may be developed that provide further information about the pattern and variations thereof.

For a better understanding of the present invention, together with other and further objects thereof, reference is made to the accompanying drawings and detailed description and its scope will be pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is Rayleigh-Benard convection pattern of stripes;

FIG. 2A is a striped pattern with a single defect;

FIG. 2B is on overlay drawing of the relative wavenumbers surrounding the defect;

FIG. 2C is an overlay drawing showing the relative orientation surround the defect;

FIG. 3 is finger print showing a characteristic striped pattern;

FIG. 4 is a histogram of the wavenumbers;

FIG. 5 is a graph comparing the local roll orientation and wavedirector magnitude corresponding to the pattern of FIG. 1, and

FIG. 6 is an block diagram of a hardware implementation of the inventive system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a pattern 2 that is locally striped. For this pattern the local pattern properties will be determined. In this preferred embodiment those local properties are the wavenumber, the orientation, and the curvature. The time variations in these local properties can also be measured by taking successive in time "snapshots" of the patterns. From such time information correlation functions and other useful data can be extracted. In addition, as described herein, pattern defects can be detected from these local properties. In a preferred embodiment, as described below, the wavenumbers are calculated in a one-dimensional pattern at each point in the image. For a two-dimensional pattern, the wavedirector is calculated at each point in the pattern, and from the wavedirector, the orientation, curvature and locations and types of defects can be determined.

In a preferred embodiment, the image of the pattern is typically held as digitized values, usually within an array of Nx by Ny pixels. Here each pixel is a point, and the value may be stored in a wide variety of bits. Eight bits being common, but more or fewer may be used to advantage with the present invention.

As is well known in the art, for a two-dimensional case, the wavenumber is the square root of the sum of the squares of the x and y Cartesian components of the wavedirector, the orientation is a function "*arctan*" of the ratio of the two components, and the curvature is the divergence of the normalized wavedirector.

Still referring to FIG. 1, the striped pattern field can be approximated locally by

$$u(\vec{x}) = A(\vec{x})\cos(\phi(\vec{x})) + mean \quad (1)$$

where $u(\vec{x})$ is the field, $A(\vec{x})$ is the slowly varying amplitude and $\phi(\vec{x})$ is the phase, and $\vec{x} = (x,y)$ is the location in the image.

In practice the mean of this field value is set to zero, and the local wavevector $\vec{k}$ is defined as the gradient function:

$$\vec{k}(\vec{x}) \equiv \vec{\nabla}\phi(\vec{x}) \quad (2)$$

Sufficiently far from defects and grain boundaries, the variations in $A(\vec{x})$ are small compared to the variations in $\phi(\vec{x})$. In that case, the components of the wavevector $\vec{k}(\vec{x})$ can be approximated using simple partial derivatives.

Specifically:

$$|k_x|^2 = -\frac{\partial_x{}^2 u(\vec{x})}{u(\vec{x})} \quad (3)$$

where $k_x(\vec{x}) = \vec{k}(\vec{x}) \bullet \hat{x}$, $\partial_x^2 \equiv \partial^2 / \partial x^2$ and $\hat{x}$ denotes the unit vector in the x direction.

Eq. (3) yields the square of the x component of the wavevector. Eq. 3 and the equivalent equation for $|k_y|^2$ yield only the squares of magnitudes the wave components k_x and k_y. From these magnitudes, the vector can be specified in any four directions in the x-y plane. However, striped patterns are locally invariant under rotations by 180 degrees, so the wavevector (k_x, k_y) is equivalent to the wavevector ($-k_x$, $-k_y$); i.e., the wavevector is actually a wavedirector field, $\overleftrightarrow{k}\left(\vec{x}\right)$ we only need to determine the sign of k_y relative to k_x. This is accomplished using a mixed partial derivative. Choose $k_x>0$, then

$$k_y = -\left|k_y\right| sign\left(\frac{\partial_{xy} u\left(\vec{x}\right)}{u\left(\vec{x}\right)}\right) \qquad (4)$$

Where $sign(v) = v/|v|$, and $|k_y|$ is determined using the equation analogous to Eq. 3.

Differentiation of the fields is most reliably and rapidly conducted by using a Fast Fourier transform (FFT) technique. For this purpose the field is transformed into Fourier space, multiplied with the respective combination of wavenumbers and transformed back to real space. It is necessary to ensure that the analyzed image is locally periodic and has no mean. For this purpose before conducting the multiplication with wavenumber combinations for the differentiation, the Fourier Transform of the image is multiplied with a filter function which sets low and high frequencies to zero. This way higher harmonics and slow variations of the mean are eliminated.

For very noisy data it is advantageous to use an additional filter. After the data is Fourier filtered, it is transformed back to real space. Then the data is thresholded from below and above generating waveforms with flat tops and bottoms, similar to a square wave. Then the data is Fourier filtered again as described above. This additional filtering has been found effective for analyzing noisy images.

When $u\left(\vec{x}\right)$ is extremely small, Eq. (3) will be very sensitive to small uncertainties due to experimental or numerical noise. This condition has been found to be quite rare in practice; however, if this situation arises, the values are screened out and replaced with an average of the neighbors. Alternatively, ratios of higher order partial derivatives may be used.

In a preferred embodiment of this invention smoothing the wavevector over small regions (of order of the size of the wavelength) may reduce the effects of noise, higher harmonics, and other effects such as amplitude variations. In this preferred embodiment the anomalous magnitudes of the component vectors can be screened and replaced by neighboring values.

With the inventive method, and as noted above, effects of noise, of higher harmonics, and of amplitude variations neglected in Eq. (1) are often noticeable. Smoothing the director field over small, contiguous regions reduces these effects. It has been found useful to analyze the director field in the complex plane, Where $\overleftrightarrow{k}\left(\vec{x}\right)=k_x+ik_y$. This director field is smoothed in two parts. First smoothed is the magnitude function $k^2\left(\vec{x}\right)=k_x^2\left(\vec{x}\right)+k_y^2\left(\vec{y}\right)$; second smoothed is the angle expression exp. $\left(i2\theta\left(\vec{x}\right)\right)$, where $\theta\left(\vec{x}\right)$ is implicitly defined through the relation exp. $\left(i\theta\left(\vec{x}\right)\right)= \overleftrightarrow{k}\left(\vec{x}\right) \Big/ \left|\overleftrightarrow{k}\left(\vec{x}\right)\right|$, Also "exp.()" is the exponential function with the natural base. These equations are well known in the art.

The smoothing is accomplished using a Gaussian blur of radius $\lambda/2$, where λ is approximately the average wavelength in the pattern. The Gaussian blur is conducted by transforming the fields into Fourier space, multiplying the fields with the Fourier transform of the filter function (Gaussian of width $\lambda/2$) and transforming back to real space. The exact width of the filter can be easily determined empirically since higher harmonics will appear as obvious modulations to the wave number field.

In practice, the smoothing techniques add another Fast Fourier Transform to the method. It has been found that in many practical application the wavedirector field need not be determined precisely, especially when the objective is to detect defects. In this case, smoothing can be substantially reduced or possibly eliminated to save computer time.

Once the wavedirector-field is determined for each point of a data field, local quantities such as the wavenumber, the orientation of the periodicity, and the curvature can be directly computed. The magnitude of the wavenumber is given by the square root of the sum of the squares of the components, the orientation is determined by the "*arctan*" of the component values, and the curvature is $C\left(\vec{x}\right)=\vec{\nabla}\bullet\hat{k}\left(\vec{x}\right)$, as known in the art where $\hat{k}$ is the unit director. The local orientation of the striped pattern may be calculated from,

$$\theta\left(\vec{x}\right) = \arctan \frac{k_y\left(\vec{x}\right)}{k_x\left(\vec{x}\right)},$$

at each point of the pattern as shown. Inspection of FIG. 1 emphasizes the large regions of straight rolls often found within the spiral defect chaos state of Rayleigh-Benard convection. With reference to FIG. 1, the large spiral 10 in the middle of the pattern can be easily identified as a disclination. The calculations of the orientation about the center of the spiral 10 shows a full rotation indicative of the disclination The local wavevector magnitude may be calculated from, $\left|\overleftrightarrow{k}\left(\vec{x}\right)\right|=\sqrt{k_x^2\left(\vec{x}\right)+k_y^2\left(\vec{x}\right)}$, at each point of FIG. 1.

The curvature may be calculated using. $C\left(\vec{x}\right) = \vec{\nabla} \bullet \hat{k}(x)$ These calculations were accomplished for the pattern in FIG. 1 in about one second on an available modern work station.

Local wavenumber calculations may be made on the pattern of FIG. 1. In those areas that the stripes are closer together higher wavenumbers occur compared to the wider apart areas. For example, in relative terms, the wavenumber at location 12 is about twice as great as that at location 14. Also, at location 16, where the stripes are approximately straight, the orientation is relatively constant compared to the spirals. These calculations of local properties are also shown and described in a paper entitled "Importance of Local Pattern Properties in Spiral Defect Chaos" by D. A. Egolf, I. V. Melnikov and E. Bodenschatz, 80:328 (1998) and incorporated herein by reference.

As an illustration of how these local pattern properties relate to the features of the pattern, FIG. 2A shows a simple pattern with a single dislocation defect moving up the page. FIG. 2B and 2C show the magnitude of the wavevector and roll curvature, respectively, as a function of position for this pattern. These drawings are overlay of each other. At the center of FIG. 2A item 23 is a dislocation. The deformation of the pattern caused by the dislocation is clear from these figures. In FIG. 2B, the "wake" 20 is an area of locally high wavenumber following the defect while small regions 24 of lower wavenumber form diagonally in front of the defect. Other contours are shown in FIG. 2B with higher wave numbers 20 and lower wave numbers 24 connected by contour portions having wavenumbers between those of 20 and 24, Referring to FIG. 2C, the small regions of high curvature 26 substantially at the shoulders of the dislocation 23.also evidence the locality of the majority of the defect deformation. The high curvature 26 surrounds a small eye 33 of lower curvature, and 26 is, in turn surrounded by a lower portion 31. The remaining part of the drawing shows contours of varying degrees of curvature. Item 25 is a higher portion, 31 is lower, The lower part of

FIG. 2C is a contour of curvatures where 29 is higher than 35, and 35 is surrounded by a higher portion. The rest of the drawing in FIG. 2C has low curvature as evident form the substantially straight lines of the pattern of FIG. 2A distant from the defect 23.

FIG. 3 is a preferred embodiment of the invention applied to a fingerprint. Areas of higher wavenumber 15 compared to lower wavenumbers 17 are quickly found by the inventive method and system. The orientation and detection of type location of defect is accomplished with the present invention and may be used to advantage for identification purposes.

FIG. 4 is a histogram forming a probability distribution (solid line) of local wavevector magnitudes 44 obtained from 300 snapshots spaced 10 minutes apart. These patterns are generated in a horizontal layer of fluid which is confined between two parallel plates separated by a length d. The upper plate is heated and the lower plate is cooled. At a sufficient temperature difference convection appears. With reference to FIG. 4, lower line CR 38 shows a limit that when crossed indicates that a particular type of instability will occur in the pattern, called a "cross-roll" for these patterns. The other line SV 40 indicates that a different type of instability, called a "skewed-varicose" will arise. The computational time was approximately five minutes to analyze three hundred images on a single processor workstation. Also shown in FIG. 4 is the wavenumber distribution 46 obtained from radially averaged power spectra. As seen the power spectra do not represent the local wavenumber distribution. Indeed, the spectra can not be used to calculate local properties.

In addition correlation functions may be calculated by known means for the wavenumber and the orientation expression $\exp\left(i2\theta\left(\vec{x}\right)\right)$. Inspection of these correlation functions provides other useful information about the order/disorder of the patterns in space and in time.

From the decay of the correlation function the correlation length can be determined. This is shown in FIG. 5 where for the exponentially decaying orientation correlation function is shown for Rayleigh-Benard convection. A similar analysis can be applied to the correlations of the wavenumber field also shown in Figure 5.

The above described inventive method can be used to advantage analyzing copolymer micro structure, magnetic domain structures, patterns in vibrating granular layers, and, as shown above, fingerprints.

FIG. 6 is an illustrative computer hardware block diagram of a preferred implementation of the inventive system. A scanner 30 brings in the image which is digitized by an A/D 32 and processed by the computer 32 which outputs a chart showing the calculated local properties of the image. In preferred embodiments the computer may be used to analyze fingerprints, calculate the local properties and identify the fingerprint from a data base of local properties.

In another preferred embodiment the system can be used to analyze interference patterns The local nature of the method allows the analysis of parts of periotic signals.

Although the invention has been described with respect to various embodiments, it should be realized this invention is also capable of a wide variety of further and other embodiments within the spirit and scope of the appended claims.

CLAIMS

What is claimed is:

1. A method for determining local properties of a striped pattern at each point of a digital image data comprising the steps of locally:
approximating the striped pattern locally as a sinusoid with an argument,
defining a local wavedirector from said sinusoid as the gradient of the argument of the sinusoid, wherein said wavedirectors for points of the digital image data define a wavedirector field.
calculating the local wavedirector field, and
determining said local properties.

2. The method as defined in claim 1, wherein the striped pattern is defined in two dimensions, further comprising the steps of:
defining said local wavedirector with vector components in each of said two dimensions
calculating magnitudes of the vector components of the local wavedirector in said two dimensions,
calculating relative signs of the vector components compared to each other, and
determining from said magnitudes and relative signs, said local properties.

3. The method as defined in claim 2 wherein said local properties comprise: wavenumber, orientation, and curvature.

4. The method as defined in claim 3, wherein said local properties include defects.

5. The method as defined in claim 4, further comprising the step of determining the positions and types of defects by the wavenumber and orientation around the part of the image.

6. The method as defined in claim 4 further comprising the step of measuring said local properties over a time sequence of images.

7. The method as defined in claim 6 further comprising the step of:

generating correlation functions of the local properties.

8. The method as defined in claim 2 further comprising the steps of smoothing said magnitudes and orientations of the wavedirector.

9. The method as defined in claim 8 wherein said smoothing comprises the step of applying a Gaussian blur of radius about $\lambda/2$, where λ is the approximate average wavelength in a subregion under investigation.

10. The method as defined in claim 2 further compromising the steps of initially Fourier filtering the digital image data.

11. The method as defined in claim 10, further comprising the steps of thresholding amplitude of said digital data, and then performing another Fourier filtering of the resulting digital data.

12. A system for determining local properties of a striped pattern at each point of a digital image data comprising locally:

means for approximating the striped pattern locally as a sinusoid with an argument,

means for defining a local wavedirector from said sinusoid as the gradient of the argument of the sinusoid, wherein said wavedirectors for points of the digital image data define a wavedirector field.

means for calculating the local wavedirector field, and means for determining, from said wavedirector field said local properties.

13. The system as defined in claim 12, wherein the striped pattern is defined in two dimensions, further comprising:

means for defining said local wavedirector with vector components in each of said two dimensions

means for calculating magnitudes of the vector components of the local wavedirector in said two dimensions,

means for calculating relative signs of the vector components compared to each other, and

means for determining from said magnitudes and relative signs, said local properties.

14. The system as defined in claim 12 wherein the means for calculating and determining comprise a computer.

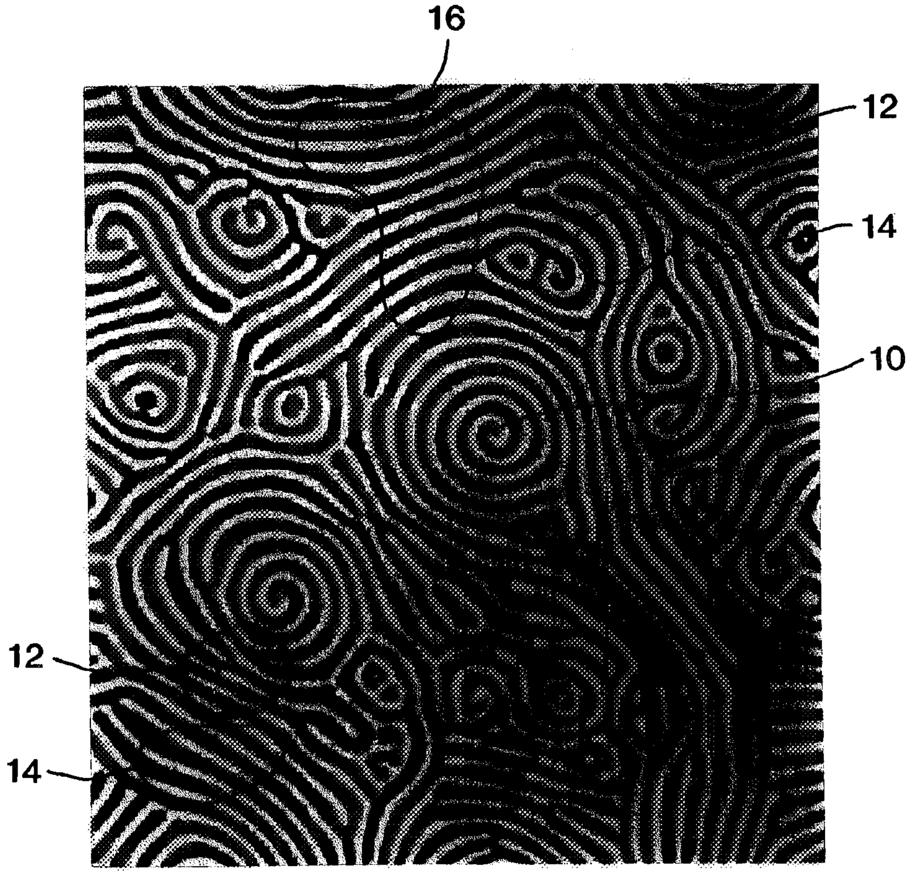

FIG. 1

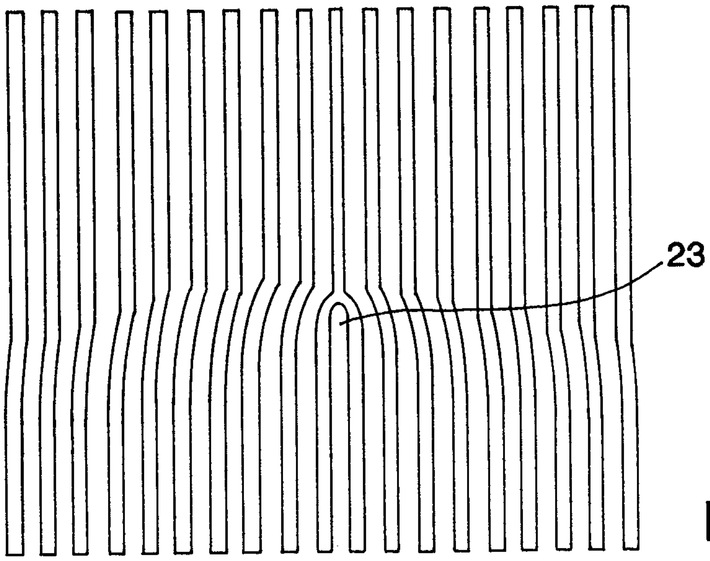

FIG. 2A

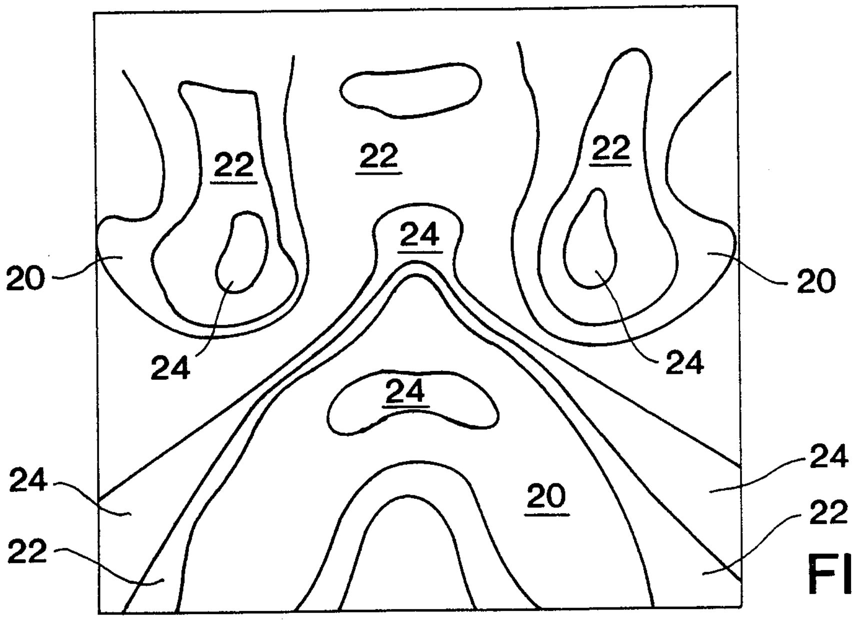

FIG. 2B

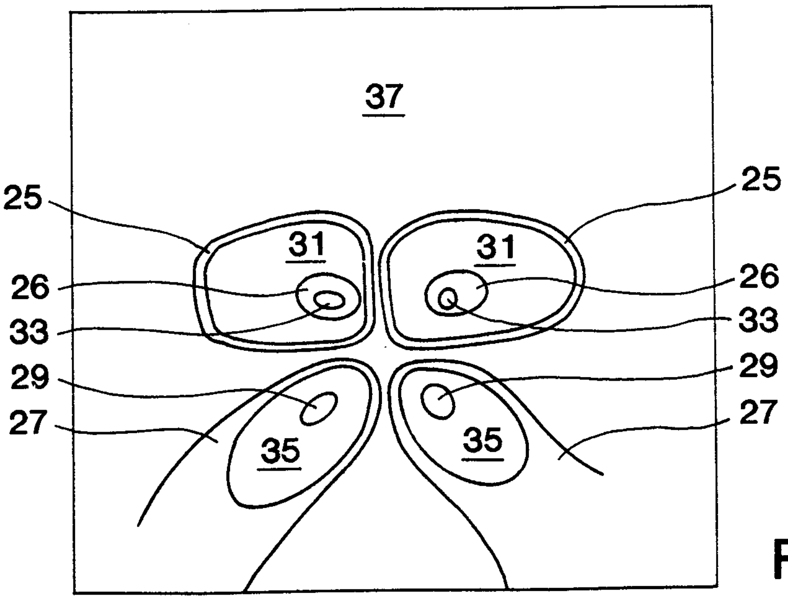

FIG. 2C

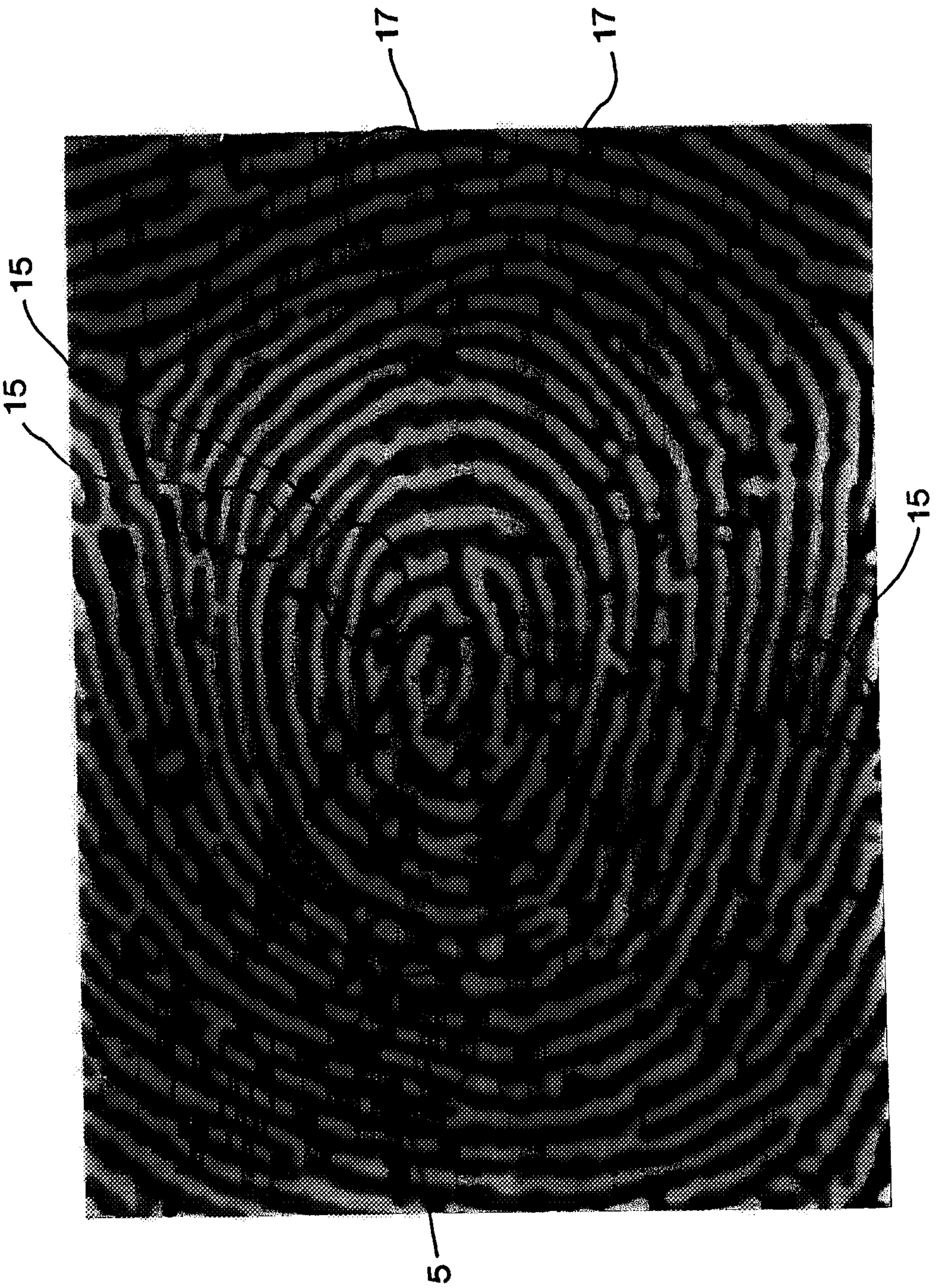

FIG. 3

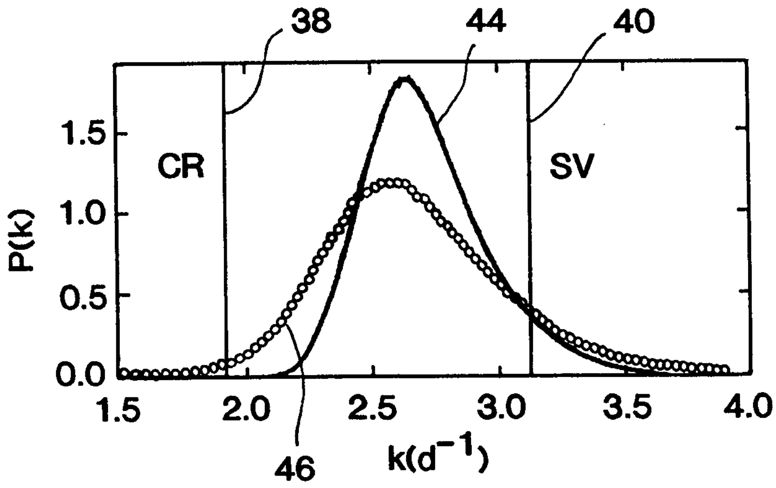

FIG. 4

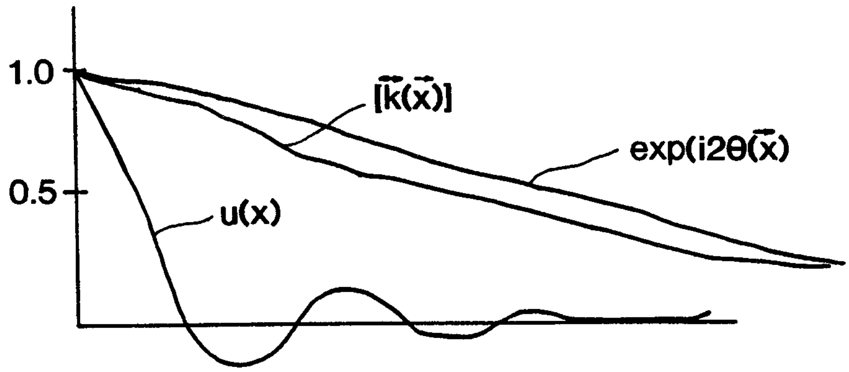

FIG. 5

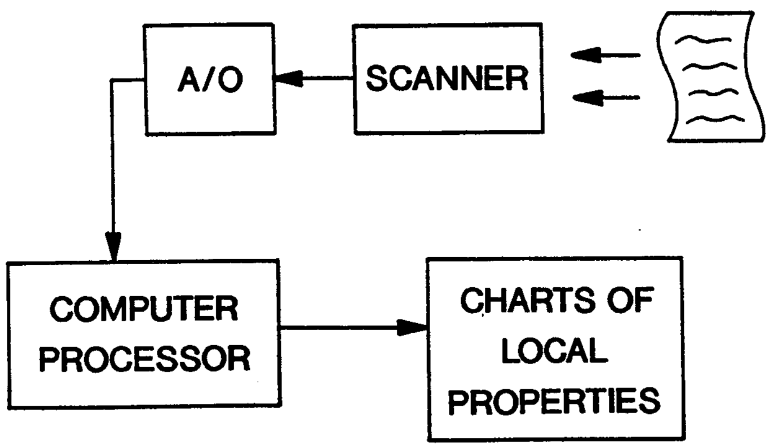

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/24815

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G06K 9/46
US CL :382/207, 141, 149, 191
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 382/207, 141, 149, 191

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, IEEE Online
Search terms: wavenumber, wavelength, local defect, striped or periodic patterns

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	US 5,513,275 A (KHALAJ et al.) 30 April 1996, col. 1, line 64-col. 2, line 7, col. 2, lines 8-43, col. 4, lines 5-46, col. 4, line 60-col. 5, line 10, col. 6, lines 53-57.	1, 2, 8,10, 12-14 ---------- 11
Y, P	US 5,802,361 A (WANG et al.) 01 September 1998, col. 9, lines 21-24	9
Y	US 5,216,481 A (MINATO) 01 June 1993, col. 3, lines 31-37	9
Y	US 4,360,269 A (IWAMOTO et al.) 23 November 1982	11

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 FEBRUARY 1999	04 MAR 1999

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	MARTIN MILLER
Facsimile No. (703) 305-3230	Telephone No. (703) 308-6604