A computer-based technique for detecting edges in gray level digital images employs fuzzy reasoning to analyze whether each pixel in an image is likely on an edge. The image is analyzed on a pixel-by-pixel basis by analyzing gradient levels of pixels in a square window surrounding the pixel being analyzed. An edge path passing through the pixel having the greatest intensity gradient is used as input to a fuzzy membership function, which employs fuzzy singletons and inference rules to assign a new gray level value to the pixel that is related to the pixel's edginess degree.

16 Claims, 7 Drawing Sheets
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FIG. 1
ID EDGE PATH THROUGH PIXEL, CALCULATE INTENSITY GRADIENT

FUZZIFICATION - USE INTENSITY GRADIENT AS INPUT TO MEMBERSHIP INPUT FUNCTION

APPLY INFEERENCE RULES USING FUZZY MEMBERSHIP OUTPUT FUNCTION AND SINGLETONS

DEFUZZIFICATION - COMBINE EDGINESS OUTPUT VALUES USING WEIGHTED AVERAGING TO OBTAIN CRISP OUTPUT VALUE FOR PIXEL

SELECT NEXT PIXEL

DONE WITH ALL PIXELS?

NO

YES

DONE

FIG. 2
FIG. 7

FIG. 8
The present invention provides such a heuristic algorithm based technique for image edge detection that has in fact been shown to outperform previous mathematical based edge detection techniques. More particularly, the technique employs fuzzy reasoning, which is a suitable framework for expressing heuristic processes applied to incomplete and imperfect image data. With fuzzy reasoning, the edge detection technique is completely adaptive with no need for selecting parameters. The use of fuzzy reasoning with the power to model and respond usefully to approximate situations is ideally suited to edge detection because the nature of the data is indeterminate at a low-level stage of processing.

In the specific method of the present invention, a multiple pixel digital image is analyzed for edges on a pixel-by-pixel basis. That is, each pixel in the image is analyzed to determine the degree to which it represents a part of an edge in the image. The analysis relies on the fact that if a pixel is on an edge, then that edge will extend in some direction away from the pixel and pixels on either side of the edge will likely have gray values that differ substantially from one another. For example, if predominantly dark, low valued pixels are on one side of the edge, predominantly light or high valued pixels will likely be on the opposite side of the edge.

With the foregoing in mind, the method of the present invention begins edge analysis of a pixel in the image by identifying an edge path running through the pixel and determining the intensity gradient on either side of the edge. To do this, a square non pixel window (a being an odd number greater or equal to 3) is preferably used with the pixel to be analyzed being located at the center of the window. There are four possible edge paths through the center pixel: horizontal, vertical and two 45 degree diagonals. Each one of these edge paths splits the non pixel window into two regions, each holding an equal number of pixels.

In the preferred embodiment, the average change of gray levels across each one of the four edge paths is computed and the edge path with the greatest change of gray levels is chosen to be used as a dimensionless input to a fuzzy membership function. The linguistic values (or labels) used for the average change of gray levels are those one heuristically might use: Small, Medium and Large. The output variable is the degree of edginess that the central pixel in the window has based on the intensity gradient value and is preferably evaluated using a known inference method referred to as the Truth Value Flow Inference (TVFI) method that uses singletons instead of fuzzy sets as used in the widely-used Mandini method. The linguistic variables (or labels) of the output value are also those one heuristically might use: Edge, Mild edge and No Edge. Simple inference rules are then used to express the dependency between the input and output values. If the grayness change is small, then the central pixel is No Edge; if the grayness change is Medium, then the central pixel is a Mild Edge; and, if the grayness change is Large, then the central pixel is Edge. A value between 0.0 and 1.0 is thus assigned to each of these three characteristics, which values represent the degree to which the pixel is an Edge, a Mild Edge or No Edge.

The final step of the method is defuzzification where the three characteristic output values for the selected edge path are combined using an averaging method to determine the crisp output value for the central pixel. Preferably, the averaging method is either an averaging union of truncated output singletons (TVFI method) or a centroid averaging process (Mandini method). The final output value of the central pixel is generated by multiplying the full grayness level and its respective edginess degree, which results in assignment of a
new gray level value to the pixel that is directly proportional to the pixel's edginess degree. The foregoing process is then repeated for all other possible windows until each pixel in the image has been characterized based on edginess.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the present invention will become apparent from the following detailed description of a preferred embodiment thereof, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a block diagram of a computer system that can be employed for detecting edges in digital images using a fuzzy reasoning based algorithm in accordance with the preferred embodiment of the present invention;

FIG. 2 is a flowchart showing the steps carried out by the edge detection algorithm of the preferred embodiment;

FIG. 3 is a schematic illustration of a 3x3 pixel window that is employed in the edge detection algorithm of the preferred embodiment to identify an edge passing through a pixel in an image having a maximum intensity gradient from one side of the edge to the opposite side of the edge;

FIG. 4 is a graph illustrating an input fuzzy membership function employed in the edge detection algorithm of the preferred embodiment;

FIG. 5 is a graph illustrating an output fuzzy membership function that is employed in the edge detection algorithm of the preferred embodiment;

FIG. 6 is a graph illustrating how an input value is employed by the input membership function to determine the singleton values (TVF method) on the respective output membership value;

FIG. 7 is a graph illustrating how the final crisp output value is generated based on the singleton output values shown in FIG. 6;

FIG. 8 is a gray-scale image to be analyzed for edges in accordance with the preferred embodiment;

FIG. 9 is an output from a first prior art edge detector algorithm of the image of FIG. 8;

FIG. 10 is an output from a second prior art edge detector algorithm of the image of FIG. 8; and

FIG. 11 is an output from the edge detector algorithm of the preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference to FIG. 1, a computer system 10 is illustrated which includes a processor 12 that is interfaced to an operating memory 14 and a storage memory 16, as is conventional. Loaded into the operating memory 14 is an edge detection software application or module 18 that is designed to detect edges in multiple bit digital images using fuzzy reasoning in accordance with a preferred embodiment of the present invention. The processor 12 can be implemented using any conventional PC, for example, but other computer systems can be employed as well.

Multiple pixel digital images to be analyzed for edges are either retrieved from the storage memory 16 or from an external image source 20 and are fed into the edge detection application 18 for analysis with an edge detection algorithm. In the specific method of the present invention, a multiple pixel digital image is analyzed for edges on a pixel-by-pixel basis. That is, each pixel in the image is analyzed to determine the degree to which the pixel likely represents a part of an edge in the image. The analysis relies on the fact that if a pixel is on an edge, then that edge will extend in some direction away from the pixel and pixels on either side of the edge will likely have gray values that differ substantially from one another. For example, if predominantly dark, low valued pixels are on one side of the edge, predominantly light or high valued pixels will likely be on the opposite side of the edge.

With the foregoing in mind and with reference to the flowchart of FIG. 2, the algorithm of the present invention begins edge analysis of a pixel in the image at step 100 by identifying an edge path running through the pixel and calculating a pixel intensity gradient on either side of the edge path. To do this, a square 3x3 pixel window (a being an odd number greater or equal to 3) is used with the pixel to be analyzed being located at the center of the window. FIG. 3 illustrates such a 3x3 pixel window W with a plurality of pixels P and a center pixel CP. The non pixels P are arbitrary labeled (i, j) where i is the window's row number (i=0, 1, 2, n-1) and j is the window's column number (j=0, 1, 2, n-1). Since n is an odd number, the center pixel CP is located at x,y coordinates i=(n-1)/2 and j=(n-1)/2.

It should be noted that the use of the window W means that some pixels along the borders of the image will not be analyzed since they cannot be surrounded by a window. However, this is of little consequence since the outside edges of the image are not typically of interest in an edge detection analysis. For example, a 3x3 window would leave a 1-pixel image margin without edge grade evaluation while a 5x5 window would generate a 2-pixel margin.

As also illustrated in FIG. 3, there are four possible edge paths EP through the center pixel: horizontal, vertical and two 45 degree diagonals. Each one of these edge paths splits the non pixel window W into two regions, each holding an equal number of pixels. In the preferred embodiment, the average change or gradient of gray levels across each one of the four edge paths is then computed and the edge path with the greatest change of gray levels S_max is chosen to be used as a dimensionless input to a fuzzy membership function. If an 8 bit gray scale image is employed a gray gradient value between 0 and 255 is generated; S_max will be a dimensionless number between 0 and 1 as it is generated by dividing the gray gradient value by 255, the highest possible gray gradient value. It should be noted that while it is preferred to compare the intensity gradients of all four possible edge paths, any lesser number of the paths could be analyzed if desired, though this would likely diminish the accuracy of the edge detection process.

The next step of the process is called fuzzification. This step involves entry of S_max into a fuzzy membership function as illustrated in FIG. 4, which shows the input membership function for a plurality of input linguistic values or characteristics that are associated with the dimensionless gray level gradient value, S_max. In the preferred embodiment, the input linguistic values (or labels) used for the average change of gray levels are those one heuristically might use: Small, Medium and Large. Thus, the graph of FIG. 4 shows the pixel gradient change S_max as a function of the degree, from 0.0 to 1.0, that the magnitude of S_max is characterized as Small, Medium and Large. The membership function therefore converts the single input into three input values, one for each label.

The next step 104 implemented by the edge detection algorithm is referred to as rule evaluation in which each of the input values generated by the input membership function is applied to an output membership function. FIG. 5 illustrates the output membership function in which inference rules are applied to the values obtained from the input membership function. The output variable m is the degree of edginess that the central pixel in the window has based on the intensity
gradient value and is preferably evaluated using a known inference method referred to as the Truth Value Flow
Inference (TVFI) method that use singletons. Other more computa-
tion intensive inference methods, such as the well-known Mandani inference method, can be used, but the TVFI method
is preferred for its simplicity that leads to a much less CPU
demanding approach. The linguistic variables (or labels) of the
output values are also those one heuristically might use: Edge, Mild Edge and No Edge. Simple inference rules are then used to express the dependency between the input and output
values. Every input value goes through the rules to lead
to its respective output value holding three weight values for
each one of the output adjectives (Edge, Mild Edge and No
Edge). It should be noted that the sum of these weight values
does not have to equal 1.0 as fuzzy reasoning is not the same
as probability.
The inference rules are as follows:
1) If the grayness change is Small, then the central pixel is
   No Edge;
2) if the grayness change is Medium, then the central pixel
   is Mild Edge; and,
3) if the grayness change is Large, then the central pixel is
   Edge.

Thus, for each pixel, the inference rules will result in three
characteristic output values, each between 0.0 and 1.0, that
represent the degree to which the pixel is No Edge, Mild Edge
and Edge, respectively.
The graph of FIG. 6 illustrates the application of the infer-
ence rules on both the input and output membership functions
that yield the final set of truncated singleton values. In the
example of FIG. 6, the input value 0.2 leads to input adjective
weight values of 0.25 for Small, 0.35 for Medium, and 0.8 for Large, Mild Medium and Small respectively; these adjective weight values and the set of
rules yield the truncated output singleton values 0.25, 0.35,
and 0.8 for the adjectives Edge, Mild and No Edge respect-
ively.

Once the truncated singleton values have been determined,
the final step 106 of the method is defuzzification where the
three characteristic output values for the selected edge path
are combined using an averaging union of singletons (TVFI
method) or a centroid averaging (Mandani method) to deter-
mine a crisp output value for the central pixel. More particu-
larly, the defuzzification process takes the union of the trun-
cated singleton values illustrated in FIG. 6, and then takes
their weighted average to generate a crisp output value of 0.71
as shown in FIG. 7. In contrast with the Mandani method, the
TVFI method does not need to determine the centroid of the
resultant fuzzy set. The final output value of the central pixel
is generated by multiplying the full grayness level (255 for
8-bit gray-scaled images) and its respective edginess degree
(a number between 0.0 and 1.0). This results in assignment of
a new gray level value to the pixel that is directly proportional
to the pixels' edginess degree. The algorithm then queries at
step 108 whether all pixel windows have been evaluated. If
not, the algorithm selects the next pixel at step 110 and returns
to step 100 to repeat the foregoing process until each pixel in
the image has been characterized based on its degree of edgi-
ness. Once all pixels have been characterized, the application
is done at step 112.

To test the effectiveness of the subject edge detection tech-
nique, the image of a compact disc (CD) shown in FIG. 8 was
used as input and analyzed using two prior art, mathematical
based edge detection algorithms and the algorithm of the sub-
ject invention. FIGS. 9 and 10 show edge detection results
generated by the prior art algorithms, known as Sobel and
Prewit, respectively, while FIG. 11 shows the edge detection
generated by the fuzzy reasoning algorithm of the subject
invention. As the images show, the edge detection perform-
ance based on fuzzy reasoning widely supersedes those
based on the prior art mathematical algorithms. For example,
tiny edges are not detected by the prior art algorithms. There
is a dark spot with tiny edges close to the center of the CD, and
the fuzzy reasoning based algorithm of the subject invention
clearly both detects and identifies it, while the prior art tech-
niques fail to even detect it. Numbers and marks on the CD are
also much clearer using the subject fuzzy reasoning edge
detector.

Although the invention has been disclosed in terms of a
preferred embodiment, and variations thereon, it will be
understood that numerous other modifications and variations
could be made thereto without departing from the scope of
the invention as set forth in the following claims.

What is claimed is:
1. A computer-based method for detecting one or more
   edges in a multiple pixel digital image comprising the steps
   of:
   a) loading a multiple pixel digital gray scale image to be
      analyzed from an external source of images into an
      operating memory of a computer;
   b) analyzing said image for edges with an image edge
detection application run by said computer, said application
comprising the steps of:
   1) selecting a pixel in said image to be analyzed;
   2) identifying a plurality of potential edge paths which pass
      through said selected pixel;
   3) calculating an average pixel intensity gradient value for
each of said edge paths by comparing a gray level value on
one side of each of said edge paths to a
gray level intensity of pixels on an opposite side of each
of said edge paths;
   4) selecting the greatest of said average pixel intensity
gradient values of said edge paths as an input to a single
fuzzy membership function and generating with said
function, a plurality of output values that are related to a
degree to which said pixel represents an edge in said
image;
   5) combining said plurality of output values using a
weighted averaging analysis comprising an averaging
union of truncated output singletons to assign a crisp
edginess value to said pixel;
   6) assigning a new edginess based gray level value to said
pixel by multiplying an original gray level value of said
selected pixel by said crisp edginess value, said new
edginess based gray level value being proportional to an
edginess degree of said selected pixel; and
   7) repeating steps (1)-(6) for additional pixels in said
image.
2. The computer-based method of claim 1, wherein four
   edge paths are identified that pass through said pixel.
3. The computer-based method of claim 1, wherein said
   average pixel intensity gradient value for each of said edge
paths is calculated by:
   a) selecting an n x n pixel window, where n is an odd number
greater than or equal to 3 and said pixel to be analyzed is
located at a center of said window;
   b) calculating a first, average pixel intensity value of pixels in
said window on a first side of said edge path;
   c) calculating a second, average pixel intensity value of pixels
in said window on a second, opposite side of said edge path;
   d) calculating a difference between said first and second val-
ues to obtain said average pixel intensity gradient value.

4. The computer-based method of claim 1, wherein said step of generating a plurality of output values with said single membership function comprises:

- employing an input membership function to generate a plurality of input values relating said average pixel intensity gradient value to a plurality of degrees of intensity;

- applying a plurality of inference rules in an output membership function that relate the plurality of intensity degrees to a corresponding plurality of edginess degrees and thereby generate said plurality of output values.

5. The computer-based method of claim 4, wherein three of said input values, three of said inference rules and three of said output values are employed; said input values being small, medium and large; said output values being no edge, mild edge and edge; and said inference rules being if the average pixel intensity gradient value is small, the pixel is not an edge; if the average pixel intensity gradient value is medium, the pixel is a mild edge; and, if the average pixel intensity gradient value is large, the pixel is an edge.

6. A computer-based method for detecting one or more edges in a multiple pixel digital image comprising the steps of:

- loading a multiple pixel digital gray scale image to be analyzed from an external source of images into an operating memory of a computer;

- analyzing said image for edges with an image edge detection application run by said computer, said application comprising the steps of:

  1) selecting a pixel in said image to be analyzed;

  2) selecting an n x n pixel window, wherein n is an odd number greater than or equal to 3 and said window includes a center pixel, wherein said center pixel is said pixel to be analyzed;

  3) identifying a plurality of edge paths that run through said center pixel and divide said window into first and second groups of pixels;

  4) for each of said edge paths, calculating a first, average pixel intensity value of pixels in said first group and a second, average pixel intensity value of pixels in said second group; and, calculating a difference between said first and second values to obtain an average pixel intensity gradient value for each said edge path;

  5) selecting the greatest of said average pixel intensity gradient values as an input to a single fuzzy membership function to generate a plurality of input values relating said average pixel intensity gradient value to a plurality of degrees of intensity;

  6) applying a plurality of inference rules in an output membership function that relate the plurality of intensity degrees to a corresponding plurality of edginess degrees and generate a plurality of output values that are related to a degree to which said center pixel represents an edge in said image;

  7) combining said plurality of output values using a weighted averaging analysis comprising an averaging union of truncated output singletons to assign a crisp edginess value to said pixel;

  8) assigning a new edginess based gray level value to said pixel by multiplying an original gray level value of said selected pixel by said crisp edginess value, said new edginess based gray level value being proportional to an edginess degree of said selected pixel; and,

  9) repeating steps (1)-(8) for additional pixels in said image.

7. The computer-based method of claim 6, wherein four edge paths are identified that pass through said pixel.
employing an input membership function to generate a plurality of input values relating said average pixel intensity gradient value to a plurality of degrees of intensity;

applying a plurality of inference rules in an output membership function that relate the plurality of intensity degrees to a corresponding plurality of edginess degrees and thereby generate said plurality of output values.

13. The computer-based method of claim 12, wherein three of said input values, three of said inference rules and three of said output values are employed; said input values being small, medium and large; said output values being no edge, mild edge and edge; and said inference rules being if the average pixel intensity gradient value is small, the pixel is not an edge; if the average pixel intensity gradient value is medium, the pixel is a mild edge; and, if the average pixel intensity gradient value is large, the pixel is an edge.

14. A computer system for detecting one or more edges in a multiple pixel digital image comprising:
a processor;
an operating memory interfaced to and readable by said processor;
an external source of multiple pixel digital gray scale images to be analyzed for edges; and,
an image edge detection application embodied in said operating memory and executable by said processor for performing process steps for retrieving a multiple pixel gray scale digital image from said external source and detecting edges in said image, said process steps comprising the steps of:
1) retrieving an image to be analyzed from said source of images;
2) selecting a pixel in said image to be analyzed;
3) selecting an n x n pixel window, where n is an odd number greater than or equal to 3 and said window includes a center pixel, wherein said center pixel is said pixel to be analyzed;
4) identifying a plurality of edge paths that run through said center pixel and divide said window into first and second groups of pixels;
5) for each of said edge paths, calculating a first, average pixel intensity value of pixels in said first group and a second, average pixel intensity value of pixels in said second group; and, calculating a difference between said first and second values to obtain an average pixel intensity gradient value for each said edge path;
6) selecting the greatest of said average pixel intensity gradient values as an input to a single fuzzy membership function to generate a plurality of input values relating said average pixel intensity gradient value to a plurality of degrees of intensity;
7) applying a plurality of inference rules in an output membership function that relate the plurality of intensity degrees to a corresponding plurality of edginess degrees and generate a plurality of output values that are related to a degree to which said center pixel represents an edge in said image;
8) combining said plurality of output values using a weighted averaging analysis comprising an averaging union of truncated output singletons to assign a crisp edginess value to said center pixel;
9) assigning a new edginess based gray level value to said pixel by multiplying an original gray level value of said selected pixel by said crisp edginess value, said new edginess based gray level value being proportional to an edginess degree of said selected pixel; and,
10) repeating steps (2)-(9) for additional pixels in said image.

15. The computer system of claim 14, wherein said application identifies four edge paths that pass through said pixel.

16. The computer-based method of claim 14, wherein three of said input values, three of said inference rules and three of said output values are employed; said input values being small, medium and large; said output values being no edge, mild edge and edge; and said inference rules being if the average pixel intensity gradient value is small, the pixel is not an edge; if the average pixel intensity gradient value is medium, the pixel is a mild edge; and, if the average pixel intensity gradient value is large, the pixel is an edge.

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