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Two-dimensional peak filter in almost linear time

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Abstract

The goal of this paper is to develop a fast algorithm for local peak filtering of two-dimensional arrays. The ambiguity of the concept of a local peak is demonstrated and additional conditions introduced that resolve it. A correct peak filter that takes into account the above conditions is developed. To evaluate effectiveness of the proposed algorithm two known algorithms for finding local maxima are described. Estimates of the computational complexity of algorithms for the best and worst cases are given. Analysis of dependency of the algorithm execution time from image size, sliding window size and a number of local maxima, is made. The results of experimental research showed that performance of the correct peak filter is higher than its incorrect counterparts.

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Keywords: local peak; peak filter; two-dimensional array; digital image; finite state machine; computational complexity

1. Introduction

Local peak filtering is the search for local maxima of a function represented as an array of its values. Peak filtering is used in numerous image processing methods as a basic operation, including nonlinear image filtering [1] and finding of non-maximal suppression of some function [2-7] or localizing points on the scale-space [8-10]. However, despite the wide spread occurence of the problem of searching for local maxima, the concept of a local peak is difficult to define unambiguously.

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Let the local peak be the maximum element of the set of array elements contained in some rectangular window. Suppose there are several maximal elements in the local area, for example, when filter the image of the chess board. Then two alternatives are possible:

- Consider all the maximum values to be peaks. In this case, the result of the image peak filtering, consisting of constant fields, will coincide with the image itself, i.e. no filtering will actually be done.
- Do not consider any of the maximum values to be a local peak. In this case, the result of peak image filtering will often consist of a small number of peaks, which is not acceptable in many applications.

In addition to the difficulties mentioned above, solving a particular problem may pose additional restrictions, which are determined by the specifics of the application domain.

Let a *region of strict maxima* be the subregion of an image with the same values of intensity, completely surrounded by elements with smaller values. Similarly, define a *region of non-strict maxima* to be a subregion of an image with the same values of intensity, surrounded by elements with smaller values in vertical or horizontal direction. By *strict peak* we assume the single element of some region of strict maxima. An *M-peak* is an element of the region of non-strict maxima such that intensity values of all its neighboring elements in a rectangular window of size $M \times M$ do not exceed the value of this element. We call this neighborhood an *M-peak neighborhood*. Generally the position of the M-peaks is determined ambiguously.

Consider a list of M-peaks of the image. We call an *M-covering* of the corresponding list a set of image elements in the neighborhood of M-peaks from the list. A list of M-peaks is called ***correct*** if each of the regions of strict maxima in the image has a non-empty intersection with the M-covering of this list. It is not difficult to see that if only strict peaks appear on the image, then the correctness of the list of M-peaks is equivalent to all such peaks being in covering of the list.

The algorithm for finding M-peaks (hereinafter *peak filtering algorithm*) is called *correct* if the result of any image processing is a correct list of M-peaks. In the case of processing of such an image that not all its M-peaks are strict peaks, the standard algorithms for peak filtering (like those presented in Section 2) are not correct.

In this paper, we present a local peak filtering algorithm that is correct in the sense of the definition introduced above. Section 2 describes two standard algorithms for peak filtering, used later to compare the effectiveness of the proposed algorithm described in Section 3. In addition to the descriptions in the corresponding sections, theoretical estimates of the efficiency of algorithms are given. Section 4 presents the results of an experimental research of the efficiency of the proposed algorithm. Conclusions are drawn in the end of the paper.

2. Well-known algorithms for peak filtering

This section presents the peak filtering algorithms used in the research of the efficiency of the proposed correct peak filter. These algorithms are not correct in the sense described above, but, first, they are able to find peaks in the local area that the correct filter should also be able to find, and, secondly, their computational complexity is easy to calculate. Thus, the described algorithms provide a good basis for the comparison.

2.1. Exhaustive enumeration filtering

In the exhaustive enumeration filtering method, local peaks are found by direct comparison of the values of the current element with the values of all elements in the rectangular window. The peak is an element which intensity value is strictly greater than the value of any neighboring element.

$0 \le j < N_2$

Algorithm M (*Exhaustive enumeration filtering*). An array $I[i,j]$, $0 \le i < N_1$, $0 \le j < N_2$, is the input, the window is defined as a rectangular region of size $M_1 \times M_2$. The output is a list P of pairs of coordinates (i,j), corresponding to the positions of local peaks in the array $I[i,j]$.

M1. [*Iterating over elements*] For all elements of array $I[i,j]$, $0 \le i < N_1$, $0 \le j < N_2$, go to M2.