Soft Morphology in the HSV Color Space: Definitions and Implementation

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Abstract

In this paper a new approach to soft color image mathematical morphology, called *soft vector morphology*, is presented. Its main characteristic is that it is compatible to soft gray-scale morphology. Furthermore, it is vector preserving technique. The primary and secondary soft vector morphological operations are defined. Then experimental results provided demonstrate that - analogously to their grayscale counterparts - soft vector morphological transforms are advantageous regarding small detail preservation and impulse noise attenuation from color images, in comparison to the corresponding standard vector morphological transforms recently introduced in Ref. 8. Finally, a new hardware FPGA structure capable of executing soft/standard vector erosion and dilation is presented. It processes two-dimensional 24-bit resolution color images by means of a 3 x 2-pixel 24-bit resolution color structuring element. Its function is fully pipelined: after initialization time it produces an output result per one clock-cycle. MAX+PLUS II software of Altera Corporation was employed for the design and simulation of the proposed hardware structure. The typical system clock frequency is 40MHz.

1. Introduction

Mathematical morphology is an image analysis and processing methodology founded by G. Matheron,[1-2] that was developed initially for binary and then for grayscale images. It is based on geometry and the mathematical theory of order. Its main characteristic is that takes into consideration the geometrical shape of the objects to be analyzed. On this account it has been proven very useful in many image processing applications, such as bio-medical and electron microscopy analysis, geological image processing and various computer vision applications. The initial form of mathematical morphology is usually referred to as *standard mathematical morphology* in the literature, in order to be discriminated by its later extensions.

Standard gray-scale morphological transforms are highly sensitive to noise in the image under process. In some applications this sensitivity may cause problems: pre-filtering to remove noise is necessary and if this prefiltering is not done very carefully may result in corruption of the shape of objects to be studied, thus degrading the overall performance of the system. Aiming at improving the behavior of standard morphological filters in noisy environments, Koskinen et al[3] introduced an extension of standard gray-scale mathematical morphology, called soft mathematical morphology. Soft morphological transforms retain most of the properties of standard morphological transforms but they are also less sensitive to impulse noise and to small variations in object shape.[3-7]

Recently, a new approach to color image mathematical morphology, called *standard vector morphology*, has been proposed in Ref. 8 It uses new supremum and infimum operators in the HSV color space. It has been characterized as a vector technique since – unlike component-wise morphology – it takes into consideration the vector nature of colors. Its transforms – unlike reduced and partial morphologies – produce unique results in all cases, so that they do not introduce ambiguity in the resultant data. Moreover, they preserve colors in the original image, i.e. they do not introduce new colors not present in the input data. Standard vector morphology is compatible to standard gray-scale morphology: it is identical to the standard gray-scale morphology when the vector dimension is one. In addition, its operations possess the same basic properties as their standard gray-scale counterparts.

In this paper a new approach to soft color image mathematical morphology, called *soft vector morphology*, is presented. This extends the standard vector morphology theory of Ref. 8 in the same way that soft gray-scale morphology extends the standard grayscale morphology theory. Soft vector morphology, like soft gray-scale morphology, aims at improving the behavior of standard vector morphological filters in noisy environments. Its main characteristic is that it is compatible to soft gray-scale morphology: it is reduced to soft gray-scale morphology when the vector dimension is one, and furthermore, its transforms possess the same basic properties as their soft gray-scale counterparts. Moreover, experimental results show that – like their gray-scale counterparts – soft vector morphological transforms are advantageous regarding small detail preservation and impulse noise attenuation in comparison to the corresponding standard vector morphological transforms.

Soft gray-scale morphological filters can be considered as a combination of morphological and rankorder filters. Thus, the threshold decomposition technique has also been proposed for their realization in VLSI.[7] This approach is hardware demanding. Its hardware complexity grows exponentially both with the structuring element and image window size and the resolution of the pixels. So far it has not been reported in the literature any design of implementing soft color image morphological filters in hardware.

A new hardware FPGA structure suitable to carry out fast the primary soft vector morphological operations is also presented in this paper. It is a pipelined array that can process two-dimensional 24-bit resolution color images, up to 4096 pixels wide by means of a six neighbor (3x2-pixel) 24-bit resolution structuring element. The MAX+PLUS II software of Altera Corporation was employed to design and simulate the proposed structure. The FPGA used is the EPF10K130VG599-3 device of Altera. After initialization time the proposed FPGA produces an output result per one clock-cycle. The typical system clock frequency is 40MHz.

2. Soft vector Morphology for Color Images

Soft vector morphology, like soft gray-scale morphology, aims at improving the behavior of standard vector morphological filters presented in Ref. 8 in noisy environments. It retains the concept of splitting the structuring element in two parts: the core and the soft boundary. It also preserves the concept of the repetition parameter *k*, which implies that the core "weights" more than the soft boundary in the calculation of the result. Finally, analogously to soft gray-scale morphology, it substitutes the infimum/supremum operators used in Ref. 8 by other vector order statistics. The definitions for the primary soft vector morphological transforms are given below.

2.1 Definitions

In the following subsections $x \Diamond k$ denotes the *k* times repetition of item x. Term multi-set is used for a collection of objects, where repetition of objects is allowed. Furthermore, a color (vector) of the HSV space is denoted by $c(h,s,v)$.

Let SB_n be an arbitrary subset of the HSV color space, which includes *n* vectors $c_1, c_2,...,c_n$. Using the conditional vector ordering relationship ($\le$) presented in Ref. 8, we form the set $SB_{n(\text{ord})}$ of the ordered values $c_{(1)}, c_{(2)},...,c_{(n)}$, i.e.

$$SB_{n(\text{ord})} = \{c_{(1)}, c_{(2)},..c_{(n)}\} c_{(1)} \le c_{(2)} \le ... \le c_{(n)}.$$

We define

$$\min{}^{(k)} SB_n = c_{(k)},\ 1 \le k \le n \tag{1}$$

$$\max{}^{(k)} SB_n = c_{(n-k+1)},\ 1 \le k \le n \tag{2}$$

Let us consider two functions $f, g : R^n \to HSV$ (two n-dimensional color images), with domains $D[f]$ and $D[g]$, respectively, where *f* denotes the image under process (the input image) and *g* denotes the structuring element. The core and the soft boundary of the structuring element $g(z)$ are denoted by $\alpha(z_\alpha)$ and $\beta(z_\beta)$, respectively, where $z_\alpha \in D[a]$, $z_\beta \in D[\beta], = D[g] \backslash D[\alpha]$ and \ denotes the set difference. Let also be $f(x) = c(h_{xf}, s_{xf}, v_{xf})$. Then:

Definition 1. Soft vector erosion of *f* by *g* at a point *x* is defined as follows:

$$\begin{aligned}(f \Theta [\beta,\alpha,k])(x) &= \min_{x:D[g_x] \subseteq D[f]}{}^{(k)} MS1 = \\ &= \min_{z_1 \in D[f] \cap D[\alpha_x], z_2 \in D[f] \cap D[\beta_x]}{}^{(k)} \{k \Diamond (f(z_1) - \alpha_x(z_1))\} \cup \{f(z_2) - \beta_x(z_2)\}\end{aligned} \tag{3}$$

where (-) denotes the *vector subtraction* operation, that is defined as

$$f(x) - g(x) = c(h_{xf} - h_{xg}, s_{xf} - s_{xg}, v_{xf} - v_{xg}) \tag{4}$$

with

$$h_{xf} - h_{xg} = 0 \text{ if } h_{xf} - h_{xg} < 0$$

$$s_{xf} - s_{xg} = 0 \text{ if } s_{xf} - s_{xg} < 0$$

$$v_{xf} - v_{xg} = 0 \text{ if } v_{xf} - v_{xg} < 0$$

Definition 2. *Soft vector dilation* of *f* by *g* at a point *x* is defined as follows:

$$\begin{aligned}(f \oplus [\beta,\alpha,k])(x) &= \max_{x:D[f] \cap D[g'_{-x}] \neq \emptyset}{}^{(k)} MS2 = \\ &= \max_{z_1 \in D[f] \cap D[\alpha'_{-x}], z_2 \in D[f] \cap D[\beta'_{-x}]}{}^{(k)} \{k \Diamond (f(z_1) - \alpha_{-x}(-z_1))\} \cup \{f(z_2) - \beta_{-x}(-z_2)\}\end{aligned} \tag{5}$$

where $g' = g(-z)$ is the reflection of *g* through the origin of spatial co-ordinates axes and (+) denotes the operation of *vector addition*, that is defined similarly to the vector subtraction operation.[8]

From definitions of standard vector morphological operations[8] and definitions 1-2 it is obvious that, like in soft gray-scale morphology, if $k = 1$ or $\alpha = g$ soft vector morphological operations are equivalent to the corresponding standard vector morphological operations.

The constraint of soft gray-scale morphology $k \le \min\{\text{Card}[g]/2, \text{Card}[\beta]\}$ for the repetition parameter *k* [3-7] is adopted in soft vector morphology, as well, in order the nature of soft vector morphological operations to be preserved (Card[X] denotes the cardinality i.e. the number of elements of set X).

Notice that in the gray-scale case, where h = undefined, $s = 0$ and v lies in the range [0,1], the operation of *subtraction (addition)* between HSV space vectors is identical to the standard arithmetic subtraction (addition). Moreover, the conditional vector ordering relationship $\le$ defined in Ref. 8 is identical to the standard arithmetic relational operator $\le$. Subsequently, in the case of gray-scale *f* and *g* the previous definitions 1-2 are reformed to those of the corresponding soft gray-scale morphological operations.

Furthermore, it can be proven that, just like their gray-scale counterparts, the defined soft vector morphological operations retain most of the properties of the corresponding standard vector morphological operations. That is extensivity - anti-extensivity, increase-ing monotony, translation invariance and duality.

From previous discussion is deduced that the proposed soft vector morphology is compatible to soft gray-scale morphology.

2.2 Application to Noise Suppression

Impulse noise exists in many practical applications. It can be generated by various sources, including human activities such as unprotected switches, industrial machines and car ignition systems. This type of noise includes the classical salt-and-pepper noise in greyscale images.

Experimental results have shown that – analogously to their gray-scale counterparts – soft vector morphological transforms are advantageous regarding small detail preservation and impulse noise attenuation from color images, in comparison to the corresponding standard vector morphological transforms of Ref. 8.

Particularly, standard vector opening can be used only for positive impulse noise attenuation and standard vector closing can be used only for negative impulse noise attenuation from color images. On the contrary, soft vector opening, analogously to soft gray-scale opening, act as filter that cuts off both, positive and negative impulses. The same holds for soft vector closing, as well. In addition, the increase of the repetition parameter k increases the capability of soft vector morphological transforms to remove impulse noise from color images and also to retain small details of the object shape in the image under process.

Figure 1 demonstrates the superiority of soft vector opening in impulse noise removal and small detail preservation, compared to standard vector opening. Positive and negative impulses have been introduced to all three vector components h, s and v, as well. As it can be seen, for k=1 standard vector opening suppresses positive impulses while enlarges negative impulses. On the contrary, soft vector opening reduces (k=2) or completely eliminates (k=4) both, positive and negative impulses, as well.

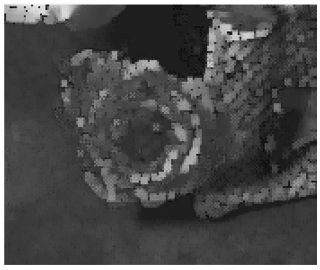
2.3 Implementation

In this subsection a new hardware FPGA structure that computes soft vector erosion and dilation is presented. It is a pipelined array capable of executing standard vector erosion and dilation, as well, since they compose special cases of their soft vector counterparts for k=1. The proposed hardware structure uses a six neighbor (3x2-pixel) 24-bit resolution structuring element (SE) and it can process two-dimensional 24-bit resolution color images, up to 4096 pixels wide. Its function is based on a version of fast mergesort algorithm, that performs in parallel the preliminary sorting of the vector sublists.

Figure 2 illustrates the operation of the proposed hardware structure in the case of soft/standard vector erosion. In the case of soft/standard vector dilation similar steps are executed.

(a) Original color image "Rose"

(b) Image corrupted by 6% positive and negative impulse noise



(c) Resulting image after standard vector opening (k=1),

(d) Resulting image after soft vector opening for k=2

(e) Resulting image after soft vector opening for k=4

Figure1.

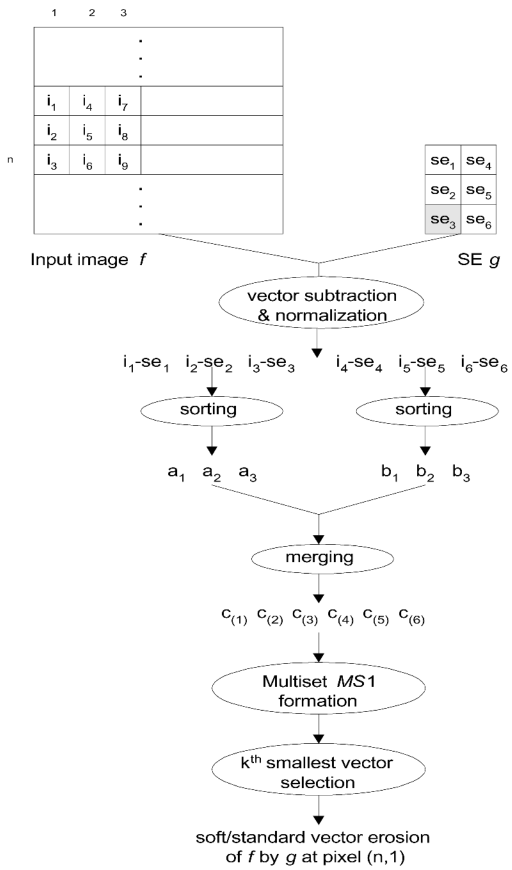


Figure 2. Steps performed during soft/standard vector erosion computation. The shaded SE area denotes the core.

The proposed FPGA structure consists of the following four stages:

In the first stage the vector values (colors) of the six structuring element pixels (se_1,...,se_6) and the vector values of the corresponding six pixels in the input image (i_1,...,i_6) are at first subtracted or added pairwise, according to the vector morphological operation (erosion or dilation) that is executed, by means of *vector subtraction or addition* operations. As it has been mentioned in Ref. 8, vector subtraction or addition may result in a color having s or v less than 0 or greater than 1 and h less than 0 or greater than 360 (see the constraint in eqn (4)). In this case the resultant value must be normalized, i.e. the value of s or v component must be adjusted to 0 or 1, respectively, while the value of h component must be adjusted to 0 or 360, respectively. Thus, the six vector sums or differences previously formed are then normalized. These normalized vector sums or differences appear simultaneously on the outputs of first stage.

In the second stage of the circuit the preliminary sorting of the vector sublists i_1 - se_1,...,i_3 - se_3 and i_4 - se_4,...,i_6 - se_6 takes place. This is achieved by means of two similar "sort3" modules that operate in parallel. The sorted vector lists a_1, a_2, a_3 and b_1, b_2, b_3 constitute the output of second stage.

In the third stage the two sorted vector sublists a_1, a_2, a_3 and b_1, b_2, b_3 that were produced by the preliminary sorting unit are merged, producing the sorted vector list $c_{(1)}$, $c_{(2)}$, ... , $c_{(6)}$, such that $c_{(1)} \leq c_{(2)} \leq ... \leq c_{(6)}$.

Finally, in the fourth stage the multiset of HSV space vectors *MS*1 or *MS*2 is produced (see eqns (3) and (5)). Then, the k^{th} smallest or largest vector of this multiset is selected, according to the value of signal "k" (repetition parameter) and to the value of signal "s" (erosion/dilation selection). The output of this stage is the result of soft or standard erosion or dilation at the pixel under consideration.

The whole procedure is fully pipelined. After initialization time the proposed FPGA produces an output result per one clock-cycle.

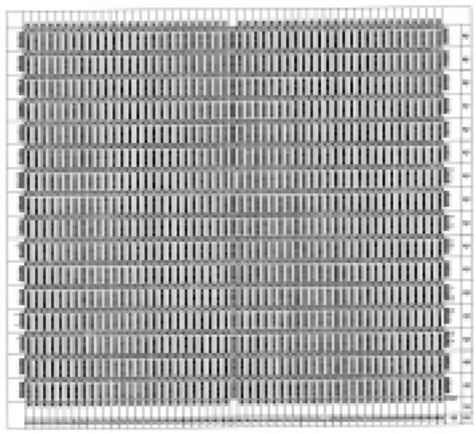


Figure 3. The LAB view of the circuit.

The proposed hardware structure was designed and successfully simulated by means of MAX+PLUS II software of Altera Corporation. The FPGA used is the EPF10K130VG599-3 device of FLEX10KA Altera device family. The typical system clock frequency is 40MHz.

The LAB (Logic Array Block) view of the circuit in the Floorplan Editor display of MAX+PLUS II is illustrated in Figure 3. This view shows the interior of the EPF10K130VG599-3 device, including the individual logic cells within each LAB and the I/O cells. Furthermore, a typical timing diagram that demonstrates the functionality of the proposed FPGA is shown in Figure 4. In the specific example the circuit computes soft vector dilation (k = 2) at each pixel of two lines m and m+1 of a 5-pixel wide input color image.

The expansion of the proposed structure in order to accommodate color images of any dimension does not increase appreciably the chip area. Furthermore, it does not affect the rate of result extraction. However, for larger size SEs, modifications that result in considerable increase of the chip area are required. For instance, for a 3 x 3-pixel SE an additional "sort3" module and an additional merging unit should be needed.

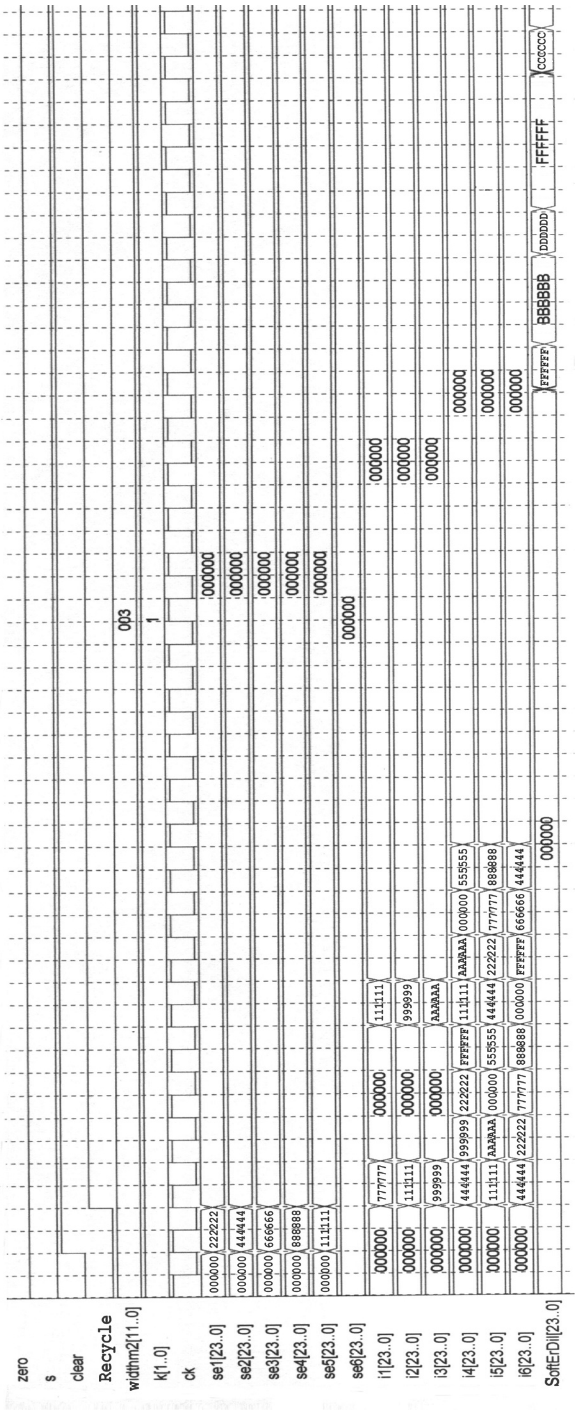


Figure 4. Timing diagram exhibiting the FPGA operation.

3. Conclusion

A new approach to soft color image morphology, that extends the standard vector morphology theory introduced in Ref. 8 has been presented in this paper. This is compatible to soft gray-scale morphology. Experimental results have been provided, which demonstrate the superiority of the defined soft vector morphological transforms in small detail preservation and color impulse noise attenuation in comparison to the corresponding standard vector morphological transforms. Furthermore, a new hardware FPGA structure suitable for the implementation of the proposed primary soft vector morphological transforms and the corresponding standard vector morphological transforms, as well, has been presented. It is a pipelined array that its function is based on a kind of fast mergesort algorithm, which performs in parallel the preliminary sorting of the vector sublists. Its typical clock frequency is 40 MHz.

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Biographies

Maria I. Vardavoulia received the Diploma Degree in Computer Engineering & Informatics from University of Patras, Greece, in 1986. For five years she worked as a professor in TEI of Kavala, Greece. From 1993 till today she works as a teacher in Lyceums. She is PhD candidate in the Dept. of Electrical & Computer Eng., DUTH, Greece. Her research interests are in machine vision. She is a member of TEE and student member of IEEE.

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