

**Human skin detection: three different
methods using correlation rules based
on dynamic color clustering**

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methods using correlation rules based
on dynamic color clustering**

This is the original version of the thesis prepared by the
candidate Rodrigo Augusto Dias Faria, such as
submitted to the Examining Committee.

To my beloved wife and daughter.

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Resumo

FARIA, R. A. D. **Detecção de pele humana: três métodos diferentes usando regras de correlação baseadas em agrupamento dinâmico de cores.** Dissertação (Mestrado) - Instituto de Matemática e Estatística, Universidade de São Paulo, São Paulo, 2018.

A pele humana é constituída a partir de uma série de camadas distintas, cada uma das quais reflete uma porção de luz incidente, depois de absorver uma certa quantidade dela pelos pigmentos que se encontram na camada. Os principais pigmentos responsáveis pela origem da cor da pele são a melanina e a hemoglobina. Há evidências de que a pigmentação da pele humana é uma adaptação para regular a penetração da radiação ultravioleta (UV) na epiderme. Como as populações se mudaram para partes do mundo com diferentes níveis de radiação UV, elas sofreram mudanças genéticas que alteraram a pigmentação da pele. Assim, tons mais escuros de pele estão, em geral, próximos à linha do Equador e dos trópicos, devido à exposição a altas radiações UV. Todos esses fatos nos dão uma ideia de quão complexo pode ser um sistema para detectar a pele humana em imagens. A detecção de pele desempenha um papel importante em uma ampla gama de aplicações em processamento de imagens e visão computacional. Em suma, existem três abordagens principais para detecção de pele: baseadas em regras, aprendizado de máquina e híbridos. Elas diferem em termos de precisão e eficiência computacional. Geralmente, as abordagens com aprendizado de máquina e as híbridas superam os métodos baseados em regras, mas exigem um conjunto de dados de treinamento grande e representativo, bem como um tempo de classificação custoso, que pode ser um fator decisivo para aplicações em tempo real. Neste trabalho, propomos uma melhoria, em três versões distintas, de um novo método de detecção de pele baseado em regras que funciona no espaço de cores YCbCr. Nossa motivação baseia-se na hipótese de que: (1) a regra original pode ser revertida e, (2) pixels de pele humana não aparecem isolados, ou seja, as operações de vizinhança são levadas em consideração. O método é uma combinação de algumas regras de correlação baseadas nessas hipóteses. Essas regras avaliam as combinações de valores de crominância Cb, Cr para identificar os pixels de pele, dependendo da forma e tamanho dos agrupamentos de cores de pele gerados dinamicamente. O método é muito eficiente em termos de esforço computacional, bem como robusto em cenas de imagens muito complexas.

Palavras-chave: detecção de pele, segmentação de pele humana, modelo de cores YCbCr, regras de correlação, agrupamento dinâmico de cores.

Abstract

FARIA, R. A. D. **Human skin detection: three different methods using correlation rules based on dynamic color clustering.** Thesis (Masters Degree) - Institute of Mathematics and Statistics, University of São Paulo, São Paulo, 2018.

Human skin is built from a series of different layers, each of which reflects a portion of impinging light, after absorbing a certain amount of it by the pigments which lie in the layer. The main pigments responsible for skin color origins are melanin and hemoglobin. There are evidences that human skin pigmentation is an adaption to regulate the penetration of Ultra Violet (UV) radiation into the epidermis. As populations moved to parts of the world with different UV radiation levels, they underwent genetic changes that modified their skin pigmentation. So, darker shades of skin are, in general, near the Equator and tropics due exposition to high UV radiation. All of these facts give us an idea on how complex can be a system to automatically detect human skin in images. Skin detection plays an important role in a wide range of image processing and computer vision applications. In short, there are three major approaches for skin detection: rule-based, machine learning and hybrid. They differ in terms of accuracy and computational efficiency. Generally, machine learning and hybrid approaches outperform the rule-based methods, but require a large and representative training dataset as well as costly classification time, which can be a deal breaker for real time applications. In this work, we propose an improvement, in three distinct versions, of a novel method on rule-based skin detection that works in the YCbCr color space. Our motivation is based on the hypothesis that: (1) the original rule can be reversed and, (2) human skin pixels do not appear isolated, i.e. neighborhood operations are taken in consideration. The method is a combination of some correlation rules based on these hypothesis. Such rules evaluate the combinations of chrominance Cb, Cr values to identify the skin pixels depending on the shape and size of dynamically generated skin color clusters. The method is very efficient in terms of computational effort as well as robust in very complex image scenes.

Keywords: skin detection, human skin segmentation, YCbCr color model, correlation rules, dynamic color clustering.

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List of Acronyms

| | |
|--------|--|
| AR | Aleix and Robert Face Database |
| CIE | Commission Internationale de l'Eclairage |
| CMY | Cyan, Magenta and Yellow |
| FERET | Face Recognition Technology database |
| GIS | Geographic Information System |
| HGR | Hand Gesture Recognition database |
| HSI | Hue, Saturation, Intensity |
| HSL | Hue, Saturation, Lightness |
| HSV | Hue, Saturation, Value |
| ID3 | Iterative Dichotomiser 3 |
| IHLS | Improved, Hue, Luminance and Saturation |
| LUT | Look-UP Table |
| NTSC | National Television System Committee |
| PAL | Phase Alternating Line |
| RBF | Radial Basis Function |
| RGB | Red, Green and Blue |
| SECAM | Sequential Color with Memory |
| SFA | Skin of FERET and AR Database |
| UCS | Uniform Chromaticity Scale |
| UCI | University of California in Irvine skin/non skin dataset |
| UV | Ultra Violet |
| VISAPP | International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications |
| YIQ | Luma, Hue and Saturation |
| YUV | Luma and Chrominance |

List of Symbols

| | |
|---------------|--|
| $f(x, y)$ | Intensity function of an image |
| W | Number of horizontal samples (lines) of an image |
| H | Number of vertical samples (columns) of an image |
| L | Number of gray-levels |
| L_{min} | The minimum gray-level of a range |
| L_{max} | The maximum gray-level of a range |
| L_n | The n -th vector channel of a pixel |
| L_i | The i -th vector value of a channel of a pixel |
| $N_4(p)$ | Four neighbors of a pixel p |
| $N_D(p)$ | Diagonal neighbors of a pixel p |
| $N_8(p)$ | Eight neighbors of a pixel p |
| AND | AND logic operator |
| OR | OR logic operator |
| XOR | XOR logic operator |
| NOT | NOT logic operator |
| T | Threshold value in image histogram split |
| T_n | Multi-threshold values in image histogram split |
| L^* | Luminance |
| a^* | Green/red axis on $L^*a^*b^*$ color model |
| b^* | Blue/yellow axis on $L^*a^*b^*$ color model |
| u^* | Green/red axis on $L^*u^*v^*$ color model |
| v^* | Blue/yellow axis on $L^*u^*v^*$ color model |
| θ | Hue angle on HSI color model |
| \max | Max operator |
| \min | Min operator |
| \mathbb{R} | Set of real numbers |
| P | A point (pixel) in an image |
| P_Y | Y component of a pixel P in $YCbCr$ model |
| Y_{Cb} | Subspace of Cb points in function of Y |
| Y_{Cr} | Subspace of Cr points in function of Y |
| T_{YCb} | Trapezoid of Y_{Cb} subspace |
| T_{YCr} | Trapezoid of Y_{Cr} subspace |
| $A_{T_{YCb}}$ | Area of Y_{Cb} trapezoid |
| $A_{T_{YCr}}$ | Area of Y_{Cr} trapezoid |

| | |
|---------------------|--|
| Y_{min} | Minimum value of Y luminance distribution |
| Y_{max} | Maximum value of Y luminance distribution |
| Y_0 | Top-left coordinate of T_{YC_r} trapezoid |
| Y_1 | Top-right coordinate of T_{YC_r} trapezoid |
| Y_2 | Top-right coordinate of T_{YC_b} trapezoid |
| Y_3 | Top-right coordinate of T_{YC_b} trapezoid |
| Y_{min} | Minimum value of Y component |
| Y_{max} | Maximum value of Y component |
| Cr_{min} | Minimum Cr value used to compute T_{YC_r} trapezoid |
| Cr_{max} | Maximum Cr value used to compute T_{YC_r} trapezoid |
| Cb_{min} | Minimum Cb value used to compute T_{YC_b} trapezoid |
| Cb_{max} | Maximum Cb value used to compute T_{YC_b} trapezoid |
| h_{Cr} | Height of T_{YC_r} trapezoid |
| h_{Cb} | Height of T_{YC_b} trapezoid |
| $H_{Cr}(P_Y)$ | Height of other T_{YC_r} coordinates |
| $H_{Cb}(P_Y)$ | Height of other T_{YC_b} coordinates |
| $\Delta_{Cr}(P_Y)$ | Distance between $(P_Y, H_{Cr}(P_Y))$ and the base of T_{YC_r} trapezoid |
| $\Delta_{Cb}(P_Y)$ | Distance between $(P_Y, H_{Cb}(P_Y))$ and the base of T_{YC_b} trapezoid |
| $\Delta'_{Cr}(P_Y)$ | Normalized distance with respect to the difference in size of the T_{YC_r} trapezoid |
| $\Delta'_{Cb}(P_Y)$ | Normalized distance with respect to the difference in size of the T_{YC_b} trapezoid |
| α | Rate between $\Delta'_{Cr}(P_Y)$ and $\Delta'_{Cb}(P_Y)$ normalized distances |
| s_f | Rate between the longer and shorter upper side of T_{YC_r} and T_{YC_b} trapezoids |
| P_{Cr} | Cr component of a pixel P |
| P_{Cb} | Cb component of a pixel P |
| P_{Cr_s} | Estimated value of P_{Cr} point |
| P_{Cb_s} | Estimated value of P_{Cb} point |
| dP_{Cr_s} | Estimated distance value of P_{Cr} point |
| dP_{Cb_s} | Estimated distance value of P_{Cb} point |
| dP_{Cr} | Distance between P_{Cr} point and Cr_{min} |
| dP_{Cb} | Distance between P_{Cb} point and Cb_{max} |
| I_P | Minimum difference between the values P_{Cr} and P_{Cb} with respect to P_{Cb_s} |
| J_P | Maximum distance between the points (P_Y, P_{Cb}) and (P_Y, P_{Cb_s}) |
| I'_P | Minimum difference between the values P_{Cr} and P_{Cb} with respect to P_{Cr_s} |
| J'_P | Maximum distance between the points (P_Y, P_{Cr}) and (P_Y, P_{Cr_s}) |
| P_{min} | Minimum percentile of the histogram of Y luminance component used to compute trapezoid coordinates |
| P_{max} | Maximum percentile of the histogram of Y luminance component used to compute trapezoid coordinates |
| argmax | Arguments of maxima operator |

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Chapter 1

Introduction

The study and understanding of human skin color date from many years ago. Edwards and Duntley (1939) were one of those who tried to precisely analyze the color formation of this particular material by means of spectrophotometry. Spectrophotometry consists of the measurement of the light reflected at each wave-length (color) of the visible spectrum. The curve obtained can be transformed by computation into a specification of the color in terms of its three definite attributes, namely, dominant wave-length, purity, and brightness.

According to Edwards and Duntley (1939), skin is built from a series of different layers (see Fig. 1.1), each of which reflects a portion of impinging light, after absorbing a certain amount of it by the pigments which lie in the layer. The light which is neither reflected nor absorbed, however, is transmitted through each successive layer to the underlying one, where absorption, reflection, and transmission again take place. The absorption bands of the pigment in each layer are thus "imprinted" on both the reflected and transmitted light from each layer. The total reflected light, consequently, has the absorption characteristics of the pigments in all the layers. This phenomena gives rise to what our eyes see as skin color.

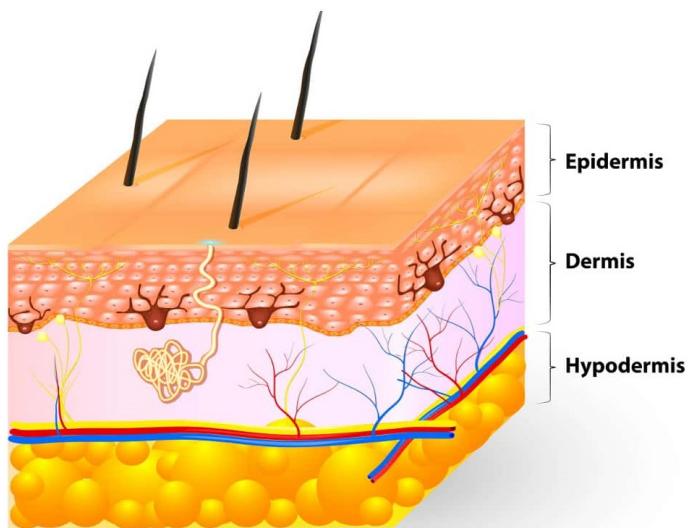


Figure 1.1: The layers of human skin. Source: Wajnberg (2018).

Edwards and Duntley (1939) observed yet that other pigments out of melanin and hemoglobin also play a role in the origin of skin color, along with an additional optical effect, designated as scattering. The pigments are melanoid – derivative of melanin –, oxyhemoglobin, and carotene. Furthermore, they stated that variations in the amount of melanin in the epidermis is responsible for the difference in human skin coloration.

Later, Anderson and Parrish (1981) provided an integrated review of the transfer of optical radiation into human skin. They (Anderson and Parrish, 1981) noticed that the epidermis provide an optical barrier, primarily by absorption of Ultra Violet (UV) radiation, and to a lesser degree, by

optical scattering. In addition, the dermis should be considered a turbid tissue matrix with which optical scattering largely defines the depth of penetration of various wavelengths radiation.

In fact, there are evidences that human skin pigmentation is an adaption for the regulation of penetration of UV radiation into the epidermis. As populations moved to parts of the world with different UV radiation levels, they underwent genetic changes that modified their skin pigmentation, a necessary fine tuning which made it possible for them to tan easily (Jablonski and Chaplin, 2000). Tanning is the ability to develop temporary melanin pigmentation in the skin in response to UV radiation and has evolved numerous times in peoples living under highly seasonal patterns of sunshine (Jablonski and Chaplin, 2010).

Therefore, a natural evolution of the skin coloration has been occurred to accommodate the physiological needs of humans as they have dispersed to regions of widely varying annual average UV radiation (Jablonski and Chaplin, 2010). This observation led Chaplin (2004) to design a model to correlate the skin reflectance to seasonal UV radiation levels and other environmental variables, with the aim of determining which variables contributed most significantly to skin reflectance. The UV radiation data recorded by satellite were combined with environmental variables and data on human skin reflectance in a geographic information system (GIS). These were then analyzed visually and statistically resulting in a predicted map of skin color reflectance (see Fig. 1.2).

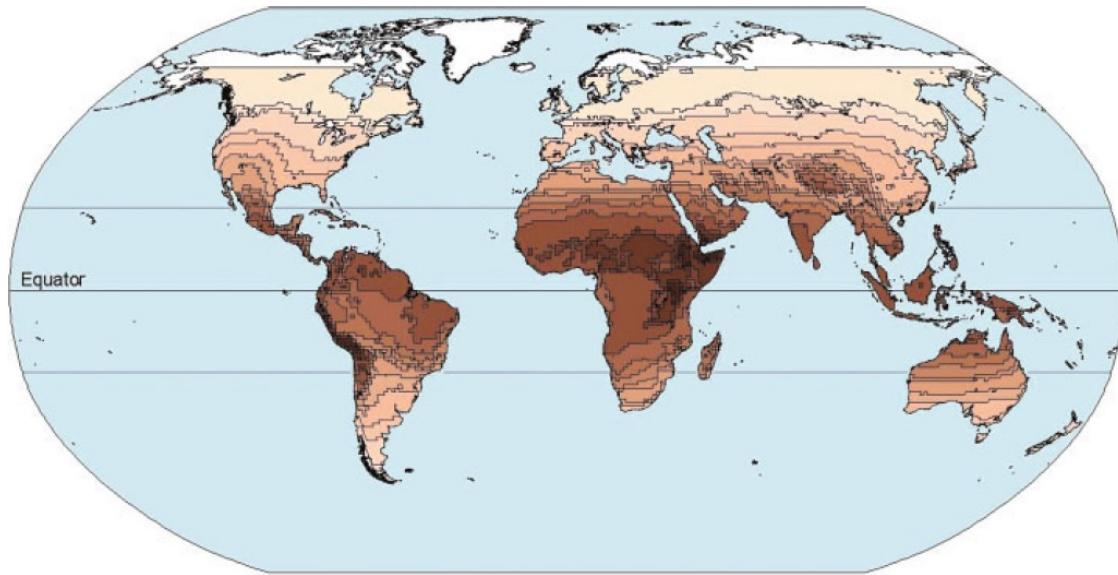


Figure 1.2: Map of skin color reflectance. The map is generalized to reduce the number of polygons. Source: Chaplin (2004).

We can clearly see darker shades of skin near the Equator and tropics due exposition to high UV radiation. This is a very singular feature of human skin, once it acts as a sun shield to protect the body from solar UV radiation (Jablonski, 2004). The large number of shades of skin shown in the map give us an idea on how complex can be a system to automatically detect human skin in images.

Skin detection can be defined as the process of identifying skin-colored pixels in an image. It plays an important role in a wide range of image processing and computer vision applications such as face detection, pornographic image filtering, gesture analysis, face tracking, video surveillance systems, medical image analysis, and other human-related image processing applications.

The problem is complex because of the numerous similar materials with human skin tone and texture, and also because of illumination conditions, ethnicity, large number of shades, sensor capturing singularities, geometric variations, etc. Because it is a primary task in image processing, additional requirements as real time processing, robustness and accuracy are also desirable.

It is worth mentioning that image processing is one of the most important tasks in a computer vision system. Its goal is to create a suitable description – typically based on shapes, textures, gray levels or color – with enough information to differentiate the objects in the scene. With this descrip-

tion, useful interpretation can be extracted from the image by means of an automatic computer system that facilitates human perception.

There is no general agreement among authors regarding where image processing stops and computer vision starts. The first, as the title says, processes the image by applying some transformations on it which will produce a more enhanced and readable image. In addition, the input and output of the process are always images. On the other hand, computer vision has the ultimate goal to use computers to emulate human vision, including learning and the ability to make inferences and take actions based on visual inputs (Gonzalez and Woods, 2002). In general, computer vision systems benefit from image processing techniques as pre-processing steps to build better applications. Thus, we can see that they definitely are not different fields, but there is an overlapping between them.

Once this work is intended to explore new methods on human skin detection, we will use techniques from both fields. Color space transformation from image processing, for example, as well as human skin segmentation and understanding as part of computer vision. This is a tentative to imitate the human visual system and its capability to recognize others from the same specie — of course, humans use other characteristics to identify other humans like shape, high, gender, and others, but skin is also part of this recognition system.

One of the powerful features used of this task is definitely skin color, which is a strong attribute and it is used in most algorithms for skin detection. It is normally used along with other features such as shape, texture, and geometry, or even as a preliminary step to classify regions of interest in an image.

The human skin color pixels have a restricted range of hues and are not deeply saturated, since the appearance of skin is formed by a combination of blood (red) and melanin (brown, yellow), which leads the human skin color to be clustered within a small area in the color space (Fleck *et al.*, 1996).

Color has the ability of functioning as a descriptor that often simplifies the identification and extraction of an object in a scene. Moreover, the ability of humans to discern thousands of tonalities and intensities compared to only a few dozen levels of gray, put the color as a strong candidate feature in computer vision and image processing applications (Gonzalez and Woods, 2002).

The human perception of colors occurs by the activation of nerve cells that send signals to the brain about brightness, hue and saturation, which are usually the features used to distinguish one color from another (Gonzalez and Woods, 2002).

The brightness gives the notion of chromatic intensity. Hue represents the dominant color perceived by an observer. Saturation refers to the relative purity or amount of white light applied to the hue. Combined, hue and saturation are known as chromaticity and, therefore, a color must be characterized by its brightness and chromaticity (Gonzalez and Woods, 2002).

Colors can be specified by mathematical models in tuples of numbers in a coordinate system and a subspace within that system where each color is represented by a single point. Such models are known as the color models (or color spaces) (Gonzalez and Woods, 2002).

The choice of a color space is also a key point of a feature-based method when using skin color as a detection cue. Due to its sensitivity to illumination, the input image is, in general, first transformed into a color space whose luminance and chrominance components can be separate to mitigate the problem (Vezhnevets *et al.*, 2003).

For the case of skin detection methods there are, basically, three approaches: rule-based, machine learning based and hybrid. They differ in terms of classification accuracy and computational efficiency. Machine learning and hybrid methods require a training set, from which the decision rules are learned. Such approaches outperform the rule-based methods but require a large and representative training dataset as well as it takes a long classification time, which can be a deal breaker for real time applications (Kakumanu *et al.*, 2007).

In this work we propose an improvement of a novel method on rule-based skin detection that works in the YCbCr color space (Brancati *et al.*, 2017). Our motivation is based on the hypothesis that the original rule can be complemented with another rule that is a reversal interpretation of the one proposed originally. Besides that, we also take in consideration that a skin pixel does not appear isolated, so we propose another variation based on neighborhood operations. The set of rules

evaluate the combinations of chrominance Cb, Cr values to identify the skin pixels depending on the shape and size of dynamically generated skin color clusters (Brancati *et al.*, 2017). The method is very efficient in terms of computational effort as well as robust in very complex image scenes.

1.1 Motivation

Perhaps this was the most iconic section I have written in this thesis. And here, first of all, I would kindly like to ask my dear Professor and advisor Roberto Hirata to excuse me for (first) summarizing the reasons that brought me to this Master's program, from a personal point of view, of course. Later, I will write down the specific reasons to choose this research topic.

When I look at the word motivation, it is impossible not to establish self-questioning such as: (i) What made you do a Master's degree in Computer Science? (ii) Why did not you pursue some other type of postgraduate course? And, of course, (iii) why did you choose this topic for the research? Responding to these questions, I must possibly bring to the reader the feeling that has moved me to this point.

I was born in a family of five siblings (seven in total) and grew up in a very poor rural zone of the countryside of Minas Gerais. I always believed that studying was the only way to change the future of my family and my own. I graduated from public high school and became a bachelor in Information Systems with a scholarship. However, I always had the dream of studying at a renowned teaching institution such as the University of São Paulo. Partly because I would like to become a Professor, something I did for a few opportunities. That answers the first question.

I am really passionate about my profession. I have ten years of experience in software development, embedded systems and, more recently, in the semiconductor industry. I felt that something was missing in my background education. The Master's degree showed me, mainly, the magic of formal mathematics and the importance it has in fundamental areas in society such as computing, engineering, physics and others. And the Institute of Mathematics and Statistics of USP played a decisive role in this respect, which answers the second question.

And last but not least, the subject of the research (third question) has been something that was attractive for us from the very beginning of the program. First, with a project on race classification in partnership with the industry. Then, with the intensification in the search for related works, with the problem of skin detection. The latter led us to the brilliant work of Brancati *et al.* (2017): a new rule-based skin detection method that works in the YCbCr color space. Here, more specifically, our motivation was to propose improvements based on the hypothesis that: (1) the original rule can be reversed and, (2) human skin pixels do not appear isolated, i.e. neighborhood operations are taken in consideration.

1.2 Contributions

In this work, we have done a comprehensive and detailed study of various methods of skin detection within those based on rules. On the basis of Brancati *et al.* (2017), seen by us as the state of the art in this field, we created variations that brought significant improvements. In addition, we analyzed the methods in question in order to provide the researchers, practitioners, enthusiasts, and other readers with a detailed understanding of the nuances involved in those methods, such as parameter selection and optimization, through a series of quantitative experiments, as well as qualitative analysis based on our observations.

Thus, we can enumerate some of the contributions that came as a result of this research project:

1. Implementation of three variations of the skin detection method proposed by Brancati *et al.* (2017) on the basis of the inversely proportional behavior of the chrominance components (Cb and Cr) of the YCbCr color model. Furthermore, extensive quantitative and qualitative experiments performed in a wide range of image datasets well-known in this field;
2. Adapted version of the neighborhood method (8-neighbors window) presented in section 4.3;

3. A grid search implementation to try different combinations of trapezoids parameters in order to optimize them (if possible) and understand those who have been used so far.

Part of our contributions was published earlier in 2018 in the *Proceedings of the 13th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications - VISAPP* (Faria and Jr., 2018).

1.3 Objectives

Skin detection is a very complex problem due the numerous similar materials with human skin tone and texture, and also because of illumination conditions, ethnicity, sensor capturing singularities, geometric variations, etc. Because it is a primary task in image processing, additional requirements as real time processing, robustness and accuracy are also desirable.

Although many advances have been observed in literature, from what we have seen until the development of this research, it is possible to say that it is not yet a completely solved problem. Basically, there are three approaches for skin detection: rule-based, machine learning based and hybrid. They differ in terms of classification accuracy and computational efficiency. In general, rule-based methods do not require a training step and they can be very competitive in terms of computational cost.

Therefore, the main objective of this research is to create or improve new methods for skin detection, according to the rule-based approach. More specifically, our main objective is to achieve improvements in the method proposed by Brancati *et al.* (2017) in order to reduce the false positive rate. In addition, we have other secondary objectives, such as:

- Publish articles with the results in renowned conference or journals in the area;
- Complete the Master's degree in three years, which includes the credits in disciplines as well as the research project and this thesis.

1.4 Organization

In this chapter we have presented the background of this work as well as the motivation, main contributions, and objectives behind it. Chapter 2 presents other relevant research works that also addresses the problem of skin detection in several distinct approaches. In Chapter 3 we provide an overview of the theoretical concepts that apply to this research. Next, in Chapter 4, we present a state of the art skin detection method recently developed by Brancati *et al.* (2017). We review the method and extend it adding more rules to enforce the constraints and seeking for a better accuracy in terms of false positive rate without hurting the performance of the original method. Then, in Chapter 5, we present the evaluation of the proposed extensions along with the original method in four widely known datasets: SFA, Pratheepan, HGR, and Compaq. In addition, a brief definition of the evaluation metrics used is shown for the sake of clarity. Finally, Chapter 6 winds up this thesis by discussing our observations along the research, focused on the experimental results, and directs the readers towards future works.

Chapter 2

Related Work

There are a large number of works of skin detection based on color information and there are a couple of them comparing different techniques and classifiers, mainly from the point of view of performance, color models, skin color modeling and different datasets (Kakumanu *et al.*, 2007; Mahmoodi and Sayedi, 2016; Vezhnevets *et al.*, 2003).

On different techniques, statistical models are those which estimate the probability that an observed pixel is associated with skin, based on a huge training dataset. One approach is the single histogram based Look-UP Table (LUT) that is capable to obtain the distribution of skin pixels in a particular color space, by using a set of training pixels (Mahmoodi and Sayedi, 2016). Considering the Red, Green, Blue (RGB) color model for instance, a histogram with 256 bins per channel - 256^3 in total - can be constructed for further counting the probability (see Eq. 2) of each possible RGB value (Jones and Rehg, 2002).

$$P(rgb) = \frac{\#counts\ of\ rgb}{total\ counts}$$

In Jones and Rehg (2002), the authors applied this technique to figure out the decision boundary of skin pixels distribution by using a 3-dimensional histogram model constructed from approximately 2 billion pixels. Those pixels were collected from 18,696 images over the internet to perform skin detection. First, visualization techniques were used to examine the shape of these distributions. Then, by examining the 3D histogram from several angles, Jones and Rehg (2002) realized that its overall shape could be inferred.

So, two different histograms for skin and non-skin in the RGB color space were calculated. Using those histograms along with training data, a surprisingly accurate pixel-wise classifier was derived. The best performance at an error rate of 88% was reached for histograms of size 32.

On the basis of the output of the skin detector, Jones and Rehg (2002) also trained a classifier to determine whether a naked person is present or not in the scene. The features used from the output to create the feature vector were:

- Percentage of pixels detected as skin
- Average probability of the skin pixels
- Size in pixels of the largest connected component of skin
- Number of connected components of skin
- Percent of colors with no entries in the skin and nonskin histograms
- Height of the image
- Width of the image

In the last step, 10,679 images were manually classified in 5,453 naked and 5,226 non-naked image sets to train a neural network classifier. The neural network outputs a number between 0 and

1, with 1 indicating a naked person in the image. The detection rate achieved was of 88%, with a false alarm rate of 11.3%.

Skin detection is sometimes used as a primary task for other applications. Hsu *et al.* (2002) have embedded skin segmentation with the purpose to build a face detector application. The algorithm first performs a lighting compensation on the R, G, and B components of the pixels of the image. Then, these color corrected components are non-linearly transformed into YCbCr space. The skin pixels are detected using an elliptical skin model with Mahalanobis distance, assuming a Gaussian distribution of skin tone color in the color space.

The experiments have shown good skin detection results, around 96% and 80% detection rate respectively on HH1 MPEG7 video and on Champion datasets, which contain images with frontal, near-frontal, half-profile and profile faces under varying backgrounds and illumination conditions. On the other hand, the results also showed a high false positive rate. This drawback is reduced further with facial feature detection procedure based on the spatial arrangement of the detected skin patches.

Another typical method explicitly defines, through a number of rules, the boundaries that delimit the grouping of skin pixels in some color space (Vezhnevets *et al.*, 2003). This was the approach adopted by Kovac *et al.* (2003) in the RGB color space, obtaining a true positive rate of 90.66%. Basically, to find out the skin cluster in the RGB color space, the skin color is determined with the following rules (Kovac *et al.*, 2003):

Skin color at uniform daylight illumination

$$R > 95, G > 40, B > 20$$

$$\max(R, G, B) - \min(R, G, B) > 15$$

$$|R - G| > 15$$

$$R > G$$

$$R > B$$

Skin color at light daylight illumination

$$R > 220, G > 210, B > 170$$

$$|R - G| \leq 15$$

$$R > B$$

$$G > B$$

They (Kovac *et al.*, 2003) also performed experiments in comparison with Hsu *et al.* (2002), where only the chromaticity channels Cb and Cr from the YCbCr color space are used. The results showed that the performance of the classifier is inferior in relation to the approach using all the three channels. Hsu *et al.* (2002) method indeed diminished the influence of noise in dark images, but in images that are captured under standard daylight illumination, they label too many pixels as skin, decreasing the performance of the face detector by increasing the number of false positive pixels (Kovac *et al.*, 2003).

Chai and Ngan (1999) proposed a similar method in YCbCr color space, where a skin color map was designed using a histogram approach based on a given set of training images. Chai and Ngan (1999) observed that the Cb and Cr distributions of skin color fall in the ranges [77, 127] and [133, 173], respectively, regardless the skin color variation in different races.

However, after an exhaustive image histogram analysis, Basilio *et al.* (2011) found that the thresholds given by Chai and Ngan (1999) was robust only against images with Caucasian people. Once their (Basilio *et al.*, 2011) purpose was to find human skin from different people races, from any place of the world, a new threshold for each chromaticity (Cb, Cr) channel has been set up,

regardless of skin color:

$$\begin{aligned} 80 \leq Cb \leq 120 \\ 133 \leq Cr \leq 173 \end{aligned}$$

The key advantage of this method is the simplicity of skin detection rules that leads to the construction of a very fast classifier. On the other hand, achieving high recognition rates with this method is difficult because it is necessary to find a good color space and empirically appropriate decision rules (Vezhnevets *et al.*, 2003).

Differently from Kovac *et al.* (2003), the authors of Yogarajah *et al.* (2011) developed a technique where the thresholds defined in the rules are dynamically adapted. The method consists of detecting the region of the eye and extracting an elliptical region to delimit the corresponding face. A Sobel filter is applied to detect the edges of the resulting region which is subjected to a dilation in order to get the optimal non-smooth regions, (i.e. eyes and mouth). The resulting image is subtracted from the elliptical image. As a result, there is a more uniform skin region where the thresholds are calculated.

Every single pixel in the colored image is classified as skin and non-skin, based on the calculated dynamic threshold values. When the algorithm detects multiple possible face regions in the image, a dynamic threshold is constructed for each of them and, subsequently, submitted to perform skin segmentation on the whole image. Finally, a logical OR operation is applied in all of the segmented regions obtained as of each dynamic threshold (Yogarajah *et al.*, 2011).

The technique was used as part of a preprocessing step in Tan *et al.* (2012) in a strategy combining a 2-dimensional density histogram and a Gaussian model for skin color detection. First, human eyes are located and, then, an elliptical mask model is used to generate the elliptical face region in the image. Due computational simplicity, a Sobel filter is employed to remove non-smooth (i.e., eyes, eye brown, mouth, etc.) regions. Then, the detected edge pixels are further submitted to a dilation operation to get the optimal non-smooth regions. Finally, a new image, that only consists of face regions, is obtained.

It is worth mentioning that the dynamic threshold with smoothed 2-D histogram is based in the assumption that the face and body of a person always share the same colors (Tan *et al.*, 2012).

Thereafter, a 2-D histogram with smoothed densities and a Gaussian model are used as features to represent the skin and non-skin distributions, respectively. They (Tan *et al.*, 2012) also applied a fusion technique that uses the product rule on the two features to obtain better skin detection results.

Experiments were carried out using three public databases: Pratheepan, ETHZ PASCAL, and Stottinger. A comparison between different color spaces as well as proposed fusion and non-fusion approaches were also established. Quantitative results are only available for Stottinger dataset with $F - measure = 0.6490$, $Precision = 0.6403$ and $Recall = 0.6580$ measures.

Naji *et al.* (2012) constructed an explicit classifier in the HSV color space for 4 different skin ethnic groups in parallel (standard skin, shadow/blackish skin, light skin and red concentrated skin and lips). After primitive segmentation, a rule-based region growth algorithm is applied, in which the output of the first layer is used as a seed, and then the final mask in other layers is constructed iteratively by neighboring skin pixels. The problem of shadow regions have been also addressed by lightening them with a skin color correction approach.

A number of 125 images were collected from two different datasets for experiments. The rate of true positive pixels reported was of 96.5% with a very low false positive rate of 0.76%.

Kawulok *et al.* (2013) combined global and local image information to construct a probability map that is used to generate the initial seed for spatial analysis of skin pixels. Seeds extracted using a local model are highly adapted to the image, which greatly improves the spatial analysis result.

In their (Kawulok *et al.*, 2013) proposal, first, human faces are detected in the input image, from where a local skin color model is learned. Skin detection is performed in the input image based on

the local model. Next, using a high-probability threshold applied in the local skin probability map, the seeds are obtained. Finally, based on the seeds gathered on previous step, the spatial analysis is carried out in the global probability map, created on the basis of the global skin color model.

Although color is not used directly in some skin detection approaches, it is one of the most decisive tools that affect the performance of algorithms (Mahmoodi and Sayedi, 2016). Despite the performance of most skin detectors is directly related to the choice of color space, Albiol *et al.* (2001) proved that the optimum performance of the skin classifiers is independent of the color space.

RGB is the most commonly used color space for storing and representing digital images, since the cameras are enabled to provide the images in such model. To reduce the influence of illumination, the RGB channels can be normalized and the third component can be removed, since it does not provide significant information (Kakumanu *et al.*, 2007). This characteristic led Bergasa *et al.* (2000) to build an adaptive and unsupervised Gaussian model to segment skin in the normalized RGB color space, using only the *r* and *g* channels.

In Jayaram *et al.* (2004), a comparative study using a Gaussian and a histogram approaches in a dataset of 805 color images in 9 different color spaces has been performed. The results revealed that the absence of the luminance component, that means, using only two channels of the color space, significantly impacts the performance. The best results were obtained in the SCT, HSI and CIELab color spaces with histogram approach.

In Chaves-González *et al.* (2010), the authors compared, under the same circumstances, the performance of 10 color spaces based on the *k*-means clustering algorithm on 15 images of the Aleix and Robert (AR) face image database (Martínez and Benavente, 1998). The ground truth images have been carefully generated by the authors. This means that parts of the photo which do not include skin color, such as hair, beard, lips, eyes, and background, were completely removed.

Experiments have been executed with *k*-means clustering method over the test set images for each of the 10 different color spaces. For each color space, Chaves-González *et al.* (2010) have done several tests with each channel lonely, using two channels – with all possible combinations –, and with the three channels.

The tests have been carried out comparing, in a detailed quantitative manner, each color space with an accurate and objective criterion. In other words, the output image produced by the *k*-means was compared, in a pixel-wise fashion, to the ground truth images to get the quantitative measures. According to the results obtained, using two channels combined did not produce good outcome. On the other hand, the results with each channel isolated were surprisingly good in comparison to the three channels fused. Lastly, the most appropriate color spaces for skin color detection observed were YCgCr, YDbDr and HSV.

A similar study on color spaces and different skin color modeling have been provided in Khan *et al.* (2012). A total of six color spaces (IHLS, HSI, RGB, normalized RGB, YCbCr and CIELab) and nine skin color modeling approaches (AdaBoost, Bayesian network, J48, Multilayer Perceptron, Naive Bayesian, Random Forest, RBF network, SVM and Histogram based) were evaluated on 8991 manually pixel-wise annotated images by means of F-measure. Khan *et al.* (2012) concluded that color space transformation does affect the overall skin performance as well as the removal of the luminance degrades the performance. In addition, classification results can be improved with the usage of lighting correction algorithms.

In Kaur and Kranthi (2012), an algorithm similar to that proposed by Kovac *et al.* (2003) have been implemented, where the boundaries that delimit the grouping of skin pixels are defined by explicit rules. After segmenting the image with the explicit rules, the algorithm also performs morphological and filtering operations to improve the accuracy of the method. The authors applied the algorithm in the YCbCr and CIELab color spaces, ignoring the Y and L luminance components, respectively. The results were more satisfactory when the algorithm was applied on CIELab. A similar technique was implemented in Shaik *et al.* (2015) and Kumar and Malhotra (2015) in the HSV and YCbCr color spaces, the latter providing the best results in both.

Finally, in Brancati *et al.* (2017), a novel rule-based skin detection method that works in the YCbCr color space based on correlation rules that evaluate the combinations of chrominance Cb,

Cr values to identify the skin pixels depending on the shape and size of dynamically generated skin color clusters was proposed. Geometrically, the clusters create trapezoids in the YCb and YCr subspaces that reflect in the inversely proportional behavior of the chrominance components. The method was compared with six well known rule-based methods in literature outperforming them in terms of quantitative performance evaluation parameters. Moreover, the qualitative analysis shows that the method is very robust in critical scenarios.

Chapter 3

Theoretical Background

The image analysis is one of the most important tasks in a computer vision system. Its goal is to create a suitable description with enough information to differentiate the objects in the scene. In general, this description is typically based on shapes, textures, gray levels or color of those objects in the image. With this description, useful interpretation can be extracted from the image by means of an automatic computer system that facilitates human perception.

There is no general agreement among authors regarding where image processing stops and computer vision starts. The first, as the title says, processes the image by applying some transformations on it such as smoothing, sharpening, noise reduction, lightening enhancement, contrasting, stretching, and compression. These will result on a more enhanced and readable image. In addition, the input and output of the process are always images (Gonzalez and Woods, 2002). On the other hand, computer vision has the ultimate goal to use computers to emulate human vision, including learning and being able to make inferences and take actions based on visual inputs (Gonzalez and Woods, 2002). In general, computer vision systems benefit from image processing techniques as preprocessing steps to build better applications. Thus, we can see that they definitely are not different fields, but there is an overlapping between them.

Once this work is intended to explore new methods on human skin detection, we will use techniques from both fields. Color space transformation from image processing, for example, as well as human skin segmentation and understanding as part of computer vision. This is a tentative to imitate the human visual system and its capability to recognize others from the same specie – of course, humans use other characteristics to identify other humans like shape, high, gender, and others, but skin is also part of this recognition system.

Therefore, in this chapter, the theoretical concepts that apply to this research are stated. First, we define and explain the concept of a digital image in section 3.1 as well as basic relationship between pixels in section 3.2. In section 3.3 we will see how image histograms are fundamental for the methods described in chapter 4 of the proposed solution. Also, the background of image segmentation, mainly for the thresholding technique is shown in section 3.4. Thereafter, a brief introduction to color models is provided in section 3.5 in order to give an overview of the main characteristics of some of the most used in the computer vision and image processing area, on which this research is based.

3.1 Digital image

By definition, an image is a two-dimensional function $f(x, y)$, where x and y are spatial coordinates, and the amplitude of f at any pair of coordinates (x, y) is called the *intensity* or *gray level* of the image at that point. The image is said digital when the function $f(x, y)$ is converted to a discrete form. This is made by a process called *digitalization*, which consists of two steps: *sampling* and *quantization* (Gonzalez and Woods, 2002).

Each element of the discrete function $f(x, y)$ is called *pixel* (picture element), where $0 \leq x \leq W - 1$ and $0 \leq y \leq H - 1$. This means that the image can be represented in a matrix form (see

Eq. 3.1), where W is the number of lines and H the number of columns of the matrix. Therefore, W and H defines the size or resolution of the image (Pedrini and Schwartz, 2008).

$$f(x, y) = \begin{bmatrix} f(0, 0) & f(0, 1) & \cdots & f(0, H-1) \\ f(1, 0) & f(1, 1) & \cdots & f(1, H-1) \\ \vdots & \vdots & \ddots & \vdots \\ f(W-1, 0) & f(W-1, 1) & \cdots & f(W-1, H-1) \end{bmatrix}$$

Usually, pixels are stored, and therefore read, in this matrix in an order known as *raster* (see Fig. 3.1). This information is important so that capture and display devices may be able to establish a common interface, and make necessary transformations in the coordinates, when needed.

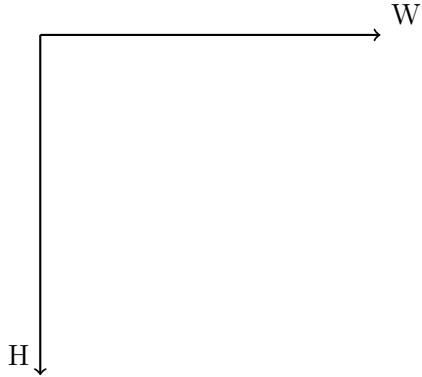


Figure 3.1: Representation of the raster order of an image. The origin coordinates $(0, 0)$ starts in the top left corner, where both axes rise. Source: proposed by the author.

In a monochromatic digital image, the value of a pixel is a scalar in the range $[L_{min}, L_{max}]$, where L is the (integer) number of gray levels (Pedrini and Schwartz, 2008).

In a multispectral image, each pixel has a vector value such that $f(x, y) = (L_1, L_2, \dots, L_n)$ where $L_{min} \leq L_i \leq L_{max}$ and $i = 1, 2, 3, \dots, n$. In general, L_i can represent different measures for each of (x, y) coordinate as well as different intervals (Pedrini and Schwartz, 2008).

A colored image is a multispectral image, where the color in each (x, y) point is given by three variables: brightness, hue and saturation (Pedrini and Schwartz, 2008). The brightness gives the notion of chromatic intensity. Hue represents the dominant color perceived by an observer. Saturation refers to the relative purity or amount of white light applied to the hue. Combined, hue and saturation are known as chromaticity and, therefore, a color must be characterized by its brightness and chromaticity (Gonzalez and Woods, 2002).

3.2 Basic relationship between pixels

There is a number of applications in image processing and computer vision that uses information of relationship among pixels to create knowledge. Some of these important relationships will be described in the following sections once we will apply it in chapter 4 further. It is worth mentioning that we defined an image as a function $f(x, y)$. In this section, when referring to a particular pixel, we will denote it in lowercase letters such as p .

3.2.1 Neighborhood

A pixel p with coordinates (x, y) has four horizontal and vertical neighbors whose coordinates are given by:

$$(x+1, y), (x-1, y), (x, y+1), (x, y-1)$$

This set of pixels, called the *4-neighbors* of p , is denoted by $N_4(p)$ (Gonzalez and Woods, 2002). See Figure 3.2 for a reference on how this neighborhood looks like.

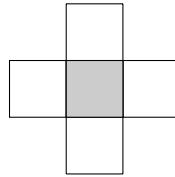


Figure 3.2: The 4-neighbors representation of a pixel p . The pixel p is centered on the grid with gray background. Source: adapted from Pedrini and Schwartz (2008).

Each pixel of the image is a unite distance from (x, y) . Some neighbors of p might lie outside of the image boundaries if (x, y) is on the border of the image (Gonzalez and Woods, 2002). Those who will use neighborhood operations in the image might take this in consideration to avoid index out of range in those regions.

The four coordinates of the diagonals of p are given by:

$$(x + 1, y + 1), (x + 1, y - 1), (x - 1, y + 1), (x - 1, y - 1)$$

This set of pixels are denoted by $N_D(p)$. When combined, the 4-neighbors and $N_D(p)$ will generate the 8-neighbors of p , known as $N_8(p)$ (Gonzalez and Woods, 2002). Formally, we have:

$$N_8(p) = N_4(p) \cup N_D(p)$$

See Figure 3.3 for a reference on how the $N_8(p)$ neighborhood looks like.

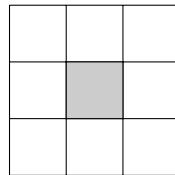


Figure 3.3: The 8-neighbors representation of a pixel p . The pixel p is centered on the grid with gray background. Source: adapted from Pedrini and Schwartz (2008).

Despite these are the most common neighbors used in applications, other different distances from p as well as connectivity can be applied. The idea of neighborhood can also be extended to 3-dimensional images where, instead of pixels, the voxels are the coordinates considered.

3.2.2 Connectivity

Connectivity between pixels is a very important concept used to establish the boundaries of objects and regions in an image. To figure out if two pixels are connected, it must be determined if they are neighbors and if their gray levels satisfy some similarity criteria, such as gray levels, color or texture equality. For instance, in a binary image, where the pixels values vary in the range $[0, 1]$, two pixels may be 4-neighbors, but they are connected if and only if they have the same value (Gonzalez and Woods, 2002).

3.2.3 Arithmetic and logic operations

Image arithmetic applies one of the standard arithmetic operations or a logical operator to two or more images. The operators are applied in a pixel-wise manner. In other words, the value of a pixel in the output image depends only on the values of the corresponding pixels in the input images. Hence, the images – or the subsets, if is the case – must be of the same size. Although image arithmetic is the most simple form of image processing, they are used extensively in a wide

range of applications and its use can potentially produce very interesting practical results. A main advantage of arithmetic operators is that the process is very simple and, therefore, fast.

The most common arithmetic operations between two pixels, say $f_1(x, y)$ and $f_2(x, y)$ of two different images f_1 and f_2 , are the addition, subtraction, multiplication and division as shown in Table 3.1 (Pedrini and Schwartz, 2008).

| Name | Operation |
|----------------|-------------------------|
| Addition | $f_1(x, y) + f_2(x, y)$ |
| Subtraction | $f_1(x, y) - f_2(x, y)$ |
| Multiplication | $f_1(x, y) * f_2(x, y)$ |
| Division | $f_1(x, y) / f_2(x, y)$ |

Table 3.1: Definition of addition, subtraction, multiplication and division arithmetic operations in two f_1 and f_2 images. Source: adapted from Pedrini and Schwartz (2008).

Addition is used often for image averaging to reduce noise. Subtraction is used frequently for static background removal. Multiplication as well as division is applied to correct gray level shading (Gonzalez and Woods, 2002).

Once the arithmetic operations can potentially produce images with values out of the gray levels given in the original images, additional effort is frequently needed to work around this situation. For instance, when adding two images, some pixels of the resulting image may be greater than 255. Similarly, when subtracting two images, some pixels may be with negative values. One way to solve this issue is, after the arithmetic operation, perform a transformation in the gray levels of the resulting image to keep them within a suitable range (Pedrini and Schwartz, 2008).

Logic operations are also useful in computer vision and image processing applications. They are applied only in binary images, while arithmetic operations can be used with higher gray levels. The terminology adopted among authors and application developers is that pixels with zero value (black color) belongs to the objects while one value (white color) corresponds to the background. Table 3.2 shows how the logic operations can be computed (Pedrini and Schwartz, 2008).

| Name | Operation |
|------|-----------------------------|
| AND | $f_1(x, y)$ AND $f_2(x, y)$ |
| OR | $f_1(x, y)$ OR $f_2(x, y)$ |
| XOR | $f_1(x, y)$ XOR $f_2(x, y)$ |
| NOT | NOT($f_1(x, y)$) |

Table 3.2: Definition of AND, OR, XOR and NOT logic operations in two f_1 and f_2 images. Source: adapted from Pedrini and Schwartz (2008).

The AND operation outputs 1 in the resulting image when both pixels, at same coordinates in the input images, are equal 1. XOR operation outputs 1 when only one of the pixels – but not both – has value 1; 0 otherwise. The result of OR operation is 1 when at least one of the pixels has 1 value. The NOT operation reverse the value of the pixel in the image (Pedrini and Schwartz, 2008).

All the logic operators can be combined to create other more complex and robust operators. They can be used to combine information between images or to extract information of regions of interest from them (Pedrini and Schwartz, 2008).

In addition to the pixel-wise processing, logic and arithmetic operations can be used for neighborhood processing. Typically, this kind of processing uses masks, where terms such as windows and filters are often used as synonym of masks. The idea of the masks is to turn the value of the

pixel a function of its own value and its neighbors. It is note mentioning that masks application are made under high computational cost. Therefore, they must be used carefully (Pedrini and Schwartz, 2008).

3.2.4 Image boundaries

When working with neighborhood operations, the mask being used, independently of its size, can fall beyond the image boundaries. In other words, this means that, for an image f , with size $W \times H$, some part of the mask operator will be located in a nonexistent pixel from an index out of the range given by $W \times H$ matrix. Figure 3.4 shows an example of this phenomena in a 10×8 image being used as input for an 4-neighbors operator.

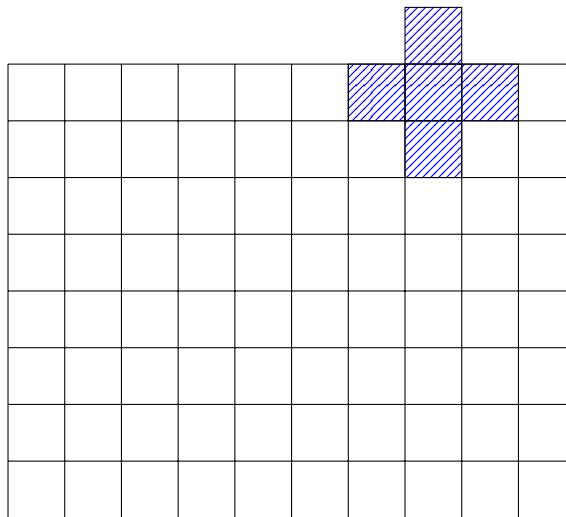


Figure 3.4: Representation of a 4-neighbors window mask going beyond image borders. Here we can solve this problem, for instance, ignoring the first and last lines and columns of the whole image during the operation. Source: adapted from Pedrini and Schwartz (2008).

There are several ways to work around this problem. One simple mechanism is to simply ignore the pixels on the border where the mask go beyond. Despite this will avoid index out of bound errors, border pixels of the image will not be looked at. Another approach is to copy the corresponding pixels from the input image. Once again, the resulting image will have some not processed pixels in the border. Another strategy is to apply a different mask for the borders, which may consider the difference in the corners as well, to perform the operation, which can turn the operation more complex and computational costly (Pedrini and Schwartz, 2008).

3.3 Image histogram

In an image processing context, the histogram of an image normally refers to a histogram of the pixel intensity values. The most common representation is a graph or plot, which gives an overall idea about the intensity distribution of an image. The foundation of a histogram can be seen as a set of bins, where each bin is representing a certain intensity value from a given range. A simple algorithm to compute a histogram of an image may examines all pixels in the image and assigns each to a bin depending on the pixel intensity. In the end, each bin will have the number of pixels of its own intensity value (Gonzalez and Woods, 2002).

For instance, in an 8-bit grayscale image there are 256 different possible intensities, and so the histogram will graphically display 256 numbers showing the counting of occurrences of those grayscale values. It is also possible to compute histograms of color images. In this particular case, the channels of the color space in use are split individually from where a separate histogram is calculated.

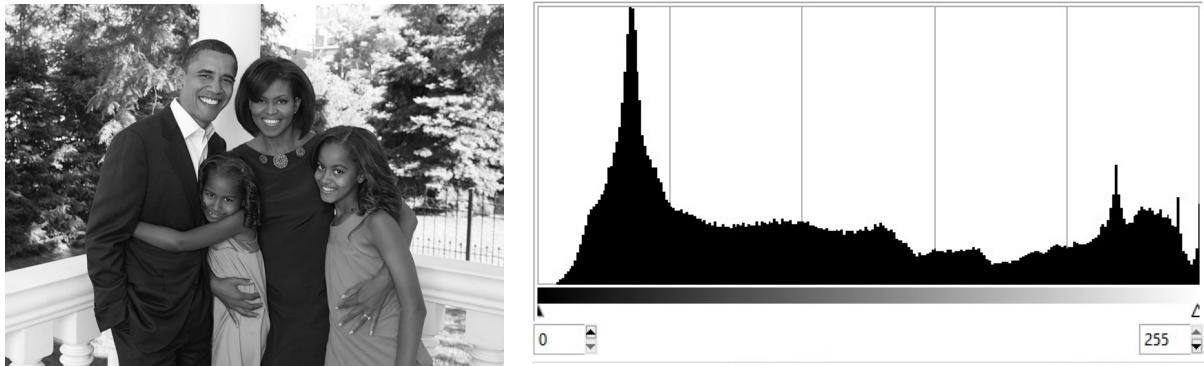


Figure 3.5: Grayscale image with its respective histogram. Left image is a sample from Pratheepan dataset, transformed to grayscale. On the right we have its histogram of pixel intensity values in the range [0, 255]. Source: Tan et al. (2012) and the author.

A histogram can be seen as a probability distribution, once the number of pixels for a given intensity level gives an estimate of the probability of occurrence of this intensity level (Gonzalez and Woods, 2002). Several statistical measures can be obtained from a histogram such that minimum and maximum values, mean, median, standard deviation, and percentiles (Pedrini and Schwartz, 2008). Those measures as well as the histogram itself are fundamental for the methods described in chapter 4 of the proposed solution.

3.4 Image segmentation

Image segmentation refers to partitioning an image into different regions that are homogeneous with respect to some image feature (Gonzalez and Woods, 2002). These regions, or objects, are the fundamental parts of an image. With respect to the human visual perception, humans use their visual sense to effortlessly partition their surrounding environment into different objects to help themselves to recognize them, guide their movements, and for almost every other task in their lives (Plataniotis and Venetsanopoulos, 2000).

Segmentation of complex images is one of the most difficult tasks in the field of image processing, where the accuracy determines whether a successful operation or not (Gonzalez and Woods, 2002). It is a heavy process that includes many interacting components that are involved with the analysis of color, shape, motion, and texture of objects in images. Despite the segmentation of images is a natural activity for the human visual system, it is definitely not easy to create algorithms whose performance is comparable to that of the human visual system (Plataniotis and Venetsanopoulos, 2000).

Image segmentation is usually the first task of any image analysis process. All subsequent tasks, such as feature extraction and object recognition rely heavily on the quality of the segmentation (Plataniotis and Venetsanopoulos, 2000). The algorithms created for image segmentation generally are based on one of two basic properties of intensity values: *discontinuity*, where abrupt changes in intensity, such as points, lines, and edges are detected, and *similarity*, whose approaches are based on regions partitioning, according to a set of predefined criteria (Gonzalez and Woods, 2002).

One of the *similarity* methods it is the thresholding: a popular and clever method used to segment regions of an image, especially in applications where speed is an important factor – that is the case for skin detection, once it is used, in general, for face detection, gesture analysis, face tracking, video surveillance systems, medical image analysis, and other human-related image processing applications. Due the simplicity of implementation, several authors apply this technique on skin detection task (Basilio et al., 2011; Chai and Ngan, 1999; Kaur and Kranthi, 2012; Kovac et al., 2003; Kumar and Malhotra, 2015; Shaik et al., 2015). Others extend this application by using adaptive thresholding (Tan et al., 2012; Yogarajah et al., 2011).

The method proposed by Brancati *et al.* (2017), where a set of dynamic correlation rules are computed to determine skin pixels, can be classified as the kind of *similarity* method. Subsequently, our proposed enhancements described in chapter 4, in a pixel-based manner, is also of this kind. Other methods detailed in chapter 2, aforementioned, and used in Brancati *et al.* (2017) as well here for comparison, are thresholding based. For that reason, a brief introduction on thresholding will be given in section 3.4.1.

3.4.1 Thresholding

Histogram thresholding is one of the simplest pixel-based techniques for image segmentation due its intuitive properties and uncomplicated implementation (Gonzalez and Woods, 2002). Roughly speaking, if an image is composed of distinct regions – that means, each region in the histogram are represented by a peak, similar to a Gaussian distribution –, adjacent regions could be split into separated groups, once adjacent peaks are likely separated by a valley (Plataniotis and Venetsanopoulos, 2000). Those valleys can be determined by means of one or more threshold values. However, to find out the threshold value that is the lower bound of a valley is definitely not a trivial task (Plataniotis and Venetsanopoulos, 2000).

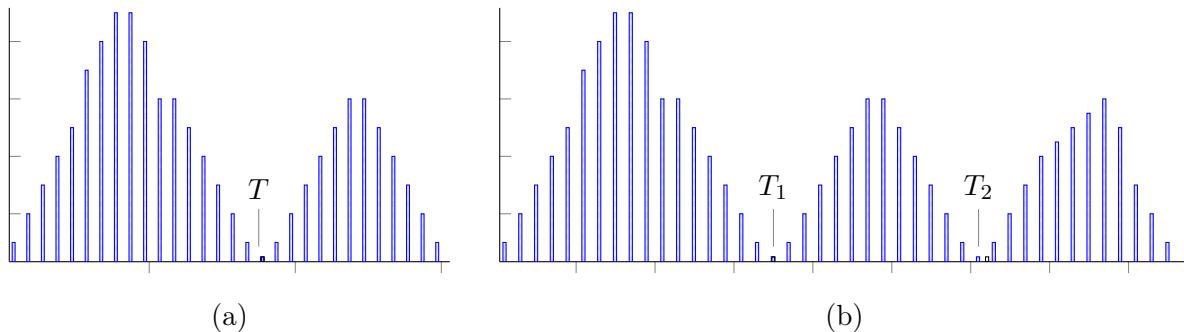


Figure 3.6: Gray level histograms that can be partitioned by (a) a single threshold, and (b) multiple thresholds. Source: adapted from (Gonzalez and Woods, 2002).

Let Figure 3.6(a) the gray levels histogram of an image $f(x, y)$. We can clearly see two dominant groups of pixels. One obvious way to separate the objects in this image is to select a threshold T that splits these groups. In other words, for every single point (x, y) , if $f(x, y) \leq T$, then (x, y) belongs to the first object (or group), otherwise it belongs to the second object. In general, one of these objects are seen as the background of the image and the other, the portion of interest in the image (Gonzalez and Woods, 2002).

The resulting image $g(x, y)$ after applying the thresholding is given by:

$$g(x, y) = \begin{cases} 0, & \text{if } f(x, y) \leq T \\ 1, & \text{otherwise} \end{cases} \quad (3.1)$$

Therefore, pixels labeled 0 corresponds to the object left of T in histogram, and pixels labeled 1 corresponds to the object right of T in histogram – or background as commonly used in literature. The *single-level thresholding* procedure that produces $g(x, y)$ image is known as *binarization* (Gonzalez and Woods, 2002).

Figure 3.6(b) shows a slightly more general case of thresholding, where three distinct groups of the histogram are split by T_1 and T_2 threshold values. Here, *multi-level thresholding* classifies a

point (x, y) as belonging to a specific object class as follows (Gonzalez and Woods, 2002):

$$g(x, y) = \begin{cases} l_1, & \text{if } f(x, y) \leq T_1 \\ l_2, & \text{if } T_1 < f(x, y) \leq T_2 \\ l_3, & \text{if } f(x, y) > T_2 \end{cases} \quad (3.2)$$

where l_1, l_2, l_3 are different gray levels used to represent each interval given by the thresholding values.

When T depends only on $f(x, y)$, that is, only on gray level values, the threshold is called *global*. When another property – e.g. the average gray level of a neighborhood centered on (x, y) – is used to define T , the threshold is called *local*. If, in addition, T depends on spatial coordinates x and y , the threshold is called *dynamic* or *adaptive* (Gonzalez and Woods, 2002). This latest is fundamental to either the method developed by Brancati *et al.* (2017) and those enhancements made by us in chapter 4. We can look for them as a particular case of adaptive thresholding to fit the skin model pixels in trapezoidal shape distributions.

3.5 Color models

The use of color images in computer vision or image processing can be motivated by two main factors. The first refers to the powerful characteristic of color to function as a descriptor that often simplifies the identification and extraction of an object in a scene. The second is related to the ability of humans to discern thousands of tonalities and intensities compared to only a few dozen levels of gray (Gonzalez and Woods, 2002).

The visual perception of color by the human eye should not vary according to the spectral distribution of the natural light incident upon an object. In other words, the color appearance of objects remains stable under different lighting conditions. This phenomenon is known as color constancy (Gevers *et al.*, 2012).

As an example, the grass of a soccer stadium remains green throughout the day, even at dusk when, from a physical point of view, sunlight has a more reddish appearance.

The human perception of colors occurs by the activation of nerve cells that send signals to the brain about brightness, hue and saturation, which are usually the features used to distinguish one color from another (Gonzalez and Woods, 2002).

The brightness gives the notion of chromatic intensity. Hue represents the dominant color perceived by an observer. Saturation refers to the relative purity or amount of white light applied to the hue. Combined, hue and saturation are known as chromaticity and, therefore, a color must be characterized by its brightness and chromaticity (Gonzalez and Woods, 2002).

Colors can be specified by mathematical models in tuples of numbers in a coordinate system and a subspace within that system where each color is represented by a single point. Such models are known as the color models (Gonzalez and Woods, 2002).

These models can be classified as of two types: the additive models in which the primary color intensities are added to produce other colors and subtractive, where colors are generated by subtracting the length of the dominant wave from the white light.

The following sections briefly describe some of the major color models, as well as their variants and main areas of application.

3.5.1 Munsell color model

Pioneer in an attempt to organize the perception of color in a color space, Albert H. Munsell was able to combine the art and science of colors in a single theory (Plataniotis and Venetsanopoulos, 2000).

The principle of equality of visual spacing between the components of the model is the essential idea of the Munsell color model. These components are hue, value, corresponding to luminance, and chroma, corresponding to saturation (Plataniotis and Venetsanopoulos, 2000).

The model is represented by a cylindrical shape and it can be seen in the Figure 3.7. The hue is arranged in the circular axis consisting of five base as well as five secondary colors, the saturation in the radial axis and the luminance in the vertical axis in a range varying from 0 to 10.

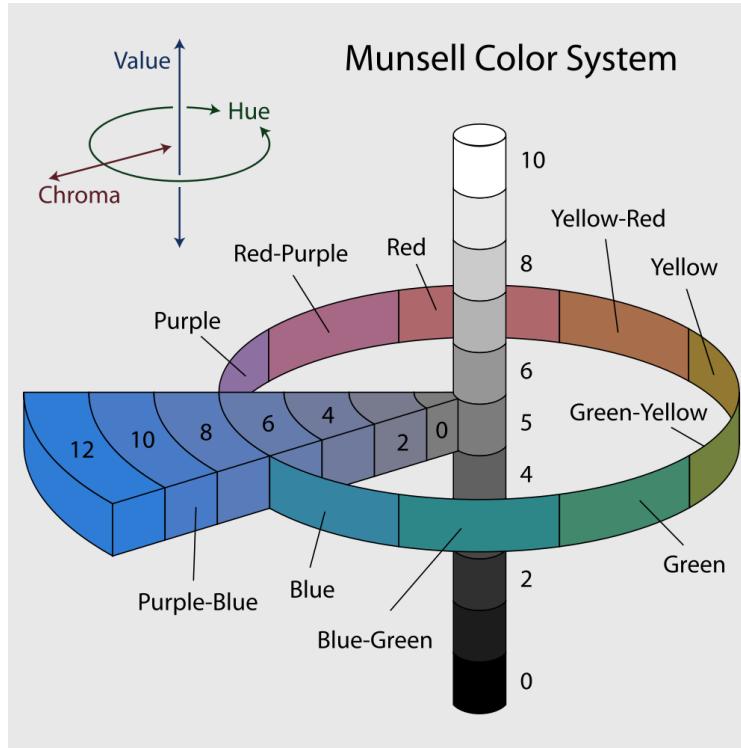


Figure 3.7: Munsell color model represented by a cylindrical shape. The hue is arranged on the circular axis consisting of five base and five secondary colors, the saturation on the radial axis and the luminance on the vertical axis in a range varying from 0 to 10. Source: Rus (2007).

3.5.2 CIE color model

In 1931, the CIE established the first mathematical model of color numerical specification, whose objective was to analyze the relationship between the physical aspects of colors in the electromagnetic spectrum and their perception by the human visual system to determine how an ordinary person perceives the color. A review of this specification was published in 1964 (Gonzalez and Woods, 2002).

The experiment that originated the standard consisted in detecting the colors perceived by an observer from a mixture of three primary colors X, Y and Z, called tristimulus values. These coordinates gave rise to the CIE XYZ color space which encompasses all the colors that can be perceived by an ordinary human being. For this reason, it is considered a device independent representation (Plataniotis and Venetsanopoulos, 2000).

The system proposed by the CIE XYZ to describe a color is based on a luminance component Y, and two additional components X and Z, that bring the chromaticity information. This system is formed by imaginary colors that can be expressed as combinations of the normalized measures shown in the equations 3.3, 3.4 and 3.5.

$$x = \frac{X}{X + Y + Z} \quad (3.3)$$

$$y = \frac{Y}{X + Y + Z} \quad (3.4)$$

$$z = \frac{Z}{X + Y + Z} \quad (3.5)$$

where $x + y + z = 1$.

Combinations of negative values and other problems related to selecting a set of real primaries are eliminated. The chromaticity coordinates x and y allow to represent all colors in a two-dimensional plane, also known as a chromaticity diagram, which can be seen in the Figure 3.8.

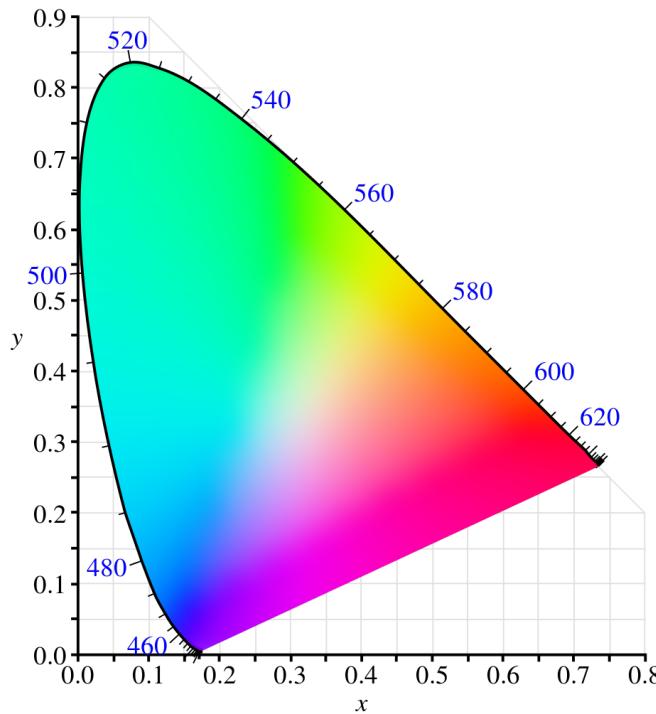


Figure 3.8: CIE 1931 chromaticity diagram. The points representing pure colors in the electromagnetic spectrum are labeled according to their wavelengths and are located along the curve from the right end of the x -axis, corresponding to the red color, to the left end of the same axis, corresponding to the violet color, forming a polygon similar to a horseshoe. The internal points correspond to all possible combinations of visible colors. Source: Ben (2009).

The coordinates $(x = 1/3, y = 1/3)$ correspond to the location of white light, also known as white point, and serve as reference in the process of image capture, coding, or reproduction.

CIE also derived and standardized two other color models based on CIE XYZ specification and, likewise, are device independent. Both are perceptually uniform, which means that equal perceptual distances separate all colors in the system (Vezhnevets *et al.*, 2003). As an example, the gray scale of the space should allow for a smooth transition between black and white.

The first one was designed to reduce the problem of perceptual non-uniformity. Some Uniform Chromaticity Scale (UCS) diagrams were proposed based on mathematical equations to transform the values XYZ or the coordinates x, y into a new set of values (u, v) , which gave rise to the 1960 CIE uv chromaticity diagram (Gevers *et al.*, 2012).

Still with unsatisfactory results, the CIE made a new change by multiplying the v component by a factor of 1.5. In addition, the brightness scale given by the Y component has been replaced by $L^* = [0, 100]$ to better represent the differences in luminosity that are equivalent. This revision originated

the CIE 1976 $L^*u^*v^*$ color model, commonly known by the acronym CIELuv (Gevers *et al.*, 2012).

In 1976 the CIE adopted a new color model, based on the L, a, b model, proposed by Richard Hunter in 1948, which best represented the uniform spacing of colors. Named CIE $L^*a^*b^*$ and known by the acronym CIELab, it is a space based on opponent colors¹ in which the color stimuli of retina is converted to distinctions between light and dark, red and green, and blue and yellow, represented by the axes L^* , a^* , and b^* , respectively (Gevers *et al.*, 2012).

3.5.3 RGB color model

The RGB model, an acronym for Red, Green, and Blue, is an additive color model in which the three primary colors red, green and blue are added to produce the others (Gonzalez and Woods, 2002).

This system was based on the trichromatic theory of Thomas Young and Hermann Helmholtz in the mid-19th century and can be represented graphically through the unit cube defined on the axes R, G and B, as illustrated in the Figure 3.9 (Plataniotis and Venetsanopoulos, 2000).

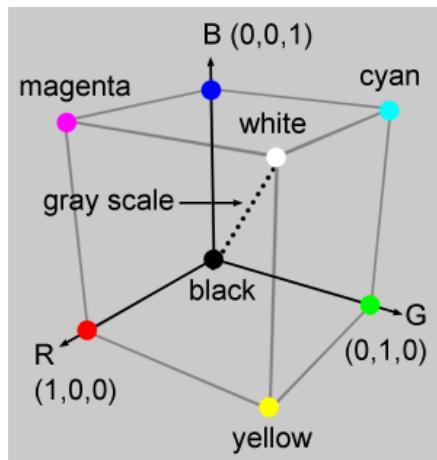


Figure 3.9: Unit cube representing the colors of the RGB model. The origin, given by the vertex $(0,0,0)$, represents the black color. The vertex $(1,1,1)$, opposite to the origin, represents the white color. The highlighted vertices on the axes represent the primary colors and the others are the complement of each. Each point inside the cube corresponds to a color that can be represented by the triple (r,g,b) , where $r,g,b \in [0,1]$. The shades of gray are represented along the main diagonal of the cube, with each point along this diagonal being formed by equal contributions of each primary color. Source: adapted from Gonzalez and Woods (2002).

It is noteworthy that there are two ways of representing the RGB space: linear and non-linear. The aforementioned system shows the non-linear model, whose abbreviation is $R'G'B'$, and is most used by devices and applications because of their similarity to the human visual system. In the literature, this system is frequently cited with the acronym RGB, which makes the nomenclature dubious, since the linear model is also called RGB and, therefore, the conversion between color spaces must be done with some caution. It is also important to note that linear RGB values are rarely used to represent an image since they are perceptually highly non-uniform (Plataniotis and Venetsanopoulos, 2000).

3.5.4 CMY color model

The CMY model is based on the complementary primary colors of the R, G, and B coordinates, which are given by Cyan, Magenta, and Yellow. Unlike RGB, is a subtractive color model, therefore, non-additive, in which colors are generated by subtracting the length of the dominant

¹Theory started around 1500 when Leonardo da Vinci concluded that colors are produced by mixing yellow and blue, green and red, and white and black. In 1950, this theory was confirmed when optically-colored signals were detected at the optical connection between the retina and the brain (Gevers *et al.*, 2012).

wave from the white light and, therefore, the resulting color corresponds to the light that is reflected (Gonzalez and Woods, 2002).

One way to get the CMY coordinates from RGB system is:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} B \\ R \\ G \end{bmatrix} + \begin{bmatrix} G \\ B \\ R \end{bmatrix} \quad (3.6)$$

or by making a change of coordinates by subtracting the primary colors R, G and B of the white color $W = (1, 1, 1)$ (Gonzalez and Woods, 2002):

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3.7)$$

Similarly to RGB, CMY is device dependent. The model is widely used in equipment that deposits colored pigments on paper, such as color printers or photocopiers. The Figure 3.10 shows how the model components are combined to generate the other colors.

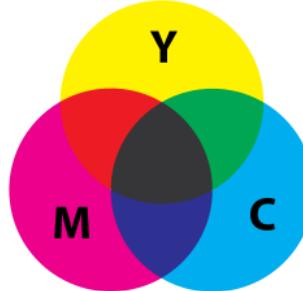


Figure 3.10: CMY subtractive color model. It is interesting to note that the intersection of yellow with magenta generates the red color, magenta with cyan generates the blue color and cyan with yellow generates the green color. Source: Rus (2008).

Overlapping the CMY primary colors in equal amounts to generate the black color typically creates a tint that is close to brown or dark green. To avoid this undesired effect, the black component is usually added to the system, represented by the letter K. This operation gives rise to a new model known as CMYK (Gonzalez and Woods, 2002).

3.5.5 Color models of the YUV family

Color models of this family is also known as orthogonal color spaces. They are able to reduce the redundancy present in RGB color channels and represent the color with statistically independent components – as independent as possible (Kakumanu *et al.*, 2007).

The acronym YUV stands to a set of color spaces of which the luminance information, represented by the Y component, is coded separately from the chrominance, given by the components U and V. The components U and V are representations of signals of the difference of the blue subtracted from luminance ($B - Y$) and red subtracted from luminance ($R - Y$). It is used to represent colors in analogue television transmission systems in the Phase Alternating Line (PAL) and Sequential Color with Memory (SECAM) (Pedrini and Schwartz, 2008).

The transformation of the RGB space to YUV is given by:

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3.8)$$

where $0 \leq R, G, B \leq 1$.

Analogous to the YUV, the YIQ model was adopted in 1950 by the National Television System Committee (NTSC), an American standard for color television signal transmission. In this model, the Y component corresponds to luminance and the components I (hue) and Q (saturation) encode the chrominance information (Pedrini and Schwartz, 2008).

The transformation of the RGB space to YIQ is given by:

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & -0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3.9)$$

where $0 \leq R, G, B \leq 1$.

Another color model of the YUV family is the YCbCr, mathematically defined by a coordinate transformation with respect to some RGB space (Pedrini and Schwartz, 2008).

The YCbCr model is widely used in digital videos. In this system, the Y component represents luminance, computed as a weighted sum of RGB values. Cb component gives the measurement of the difference between the blue color and a reference value, similar to the Cr component which is the measurement of the difference between the red color and a reference value (Pedrini and Schwartz, 2008).

The transformation of the RGB space to YCbCr is given by:

$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.169 & -0.331 & 0.5 \\ 0.5 & -0.419 & -0.081 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3.10)$$

3.5.6 Color models of the HSI family

Hue, Saturation, and Intensity (HSI) models are best suited for image processing applications from the point of view pf the user, due the correlation with human perception of the color (Plataniotis and Venetsanopoulos, 2000).

In this model, as in YIQ, the intensity given by I component is decomposed from the chrominance information, represented by the hue (H) and saturation (S) (Plataniotis and Venetsanopoulos, 2000). The combination of these components results in a pyramidal structure which can be seen in Figure 3.11.

The transformation of the components of the RGB space to HSI is given by the equations:

$$\begin{aligned} \theta &= \cos^{-1} \left(\frac{(R - G) + (R - B)}{2\sqrt{(R - G)^2 + (R - B)(G - B)}} \right) \\ H &= \begin{cases} \theta, & \text{if } B \leq G \\ 360 - \theta, & \text{otherwise} \end{cases} \\ S &= 1 - \frac{3\min(R, G, B)}{R + G + B} \\ I &= \frac{R + G + B}{3} \end{aligned} \quad (3.11)$$

It is important to note that the values R, G and B must be normalized in the interval between 0 and 1. The intensity I and the saturation S are also normalized between 0 and 1.

Another model of this family is formed by the components Hue, Saturation and Value (HSV) and its three-dimensional graphical representation is a hexagonal pyramid derived from the RGB cube (Pedrini and Schwartz, 2008). Value, in this context, is the luminance component.

The various hue shades are represented at the top of the pyramid, the saturation is measured along the horizontal axis and value is measured along the vertical axis, which passes through the center of the pyramid. The hue, which corresponds to the edges around the vertical axis, varies

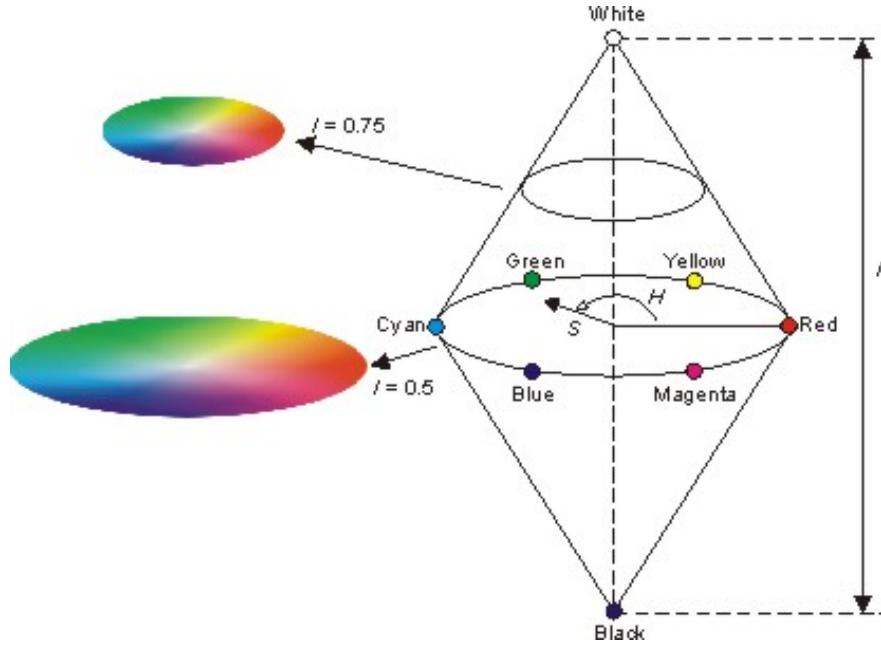


Figure 3.11: Graphical representation of the HSI model. The hue describes the color itself, in the form of an angle θ , where $\theta \in [0, 360]$. Red is at 0 degree, yellow at 60, green at 120, and so on. The saturation component, which varies between 0 and 1, indicates how much color is polluted with white color. The intensity scale is between [0, 1], where 0 means black and 1, white. Source: [Ice \(2016\)](#).

from 0 (red) to 360 degrees and the angle between the vertices is 60 degrees. The saturation varies from 0 to 1 and is represented as the ratio of the purity of a given hue to its maximum purity, that is, when $S = 1$. Value varies from 0, at the peak of the pyramid representing the black color, to 1 at the base, where the intensities of the colors are maximum (Pedrini and Schwartz, 2008).

The transformation of the components of the RGB space to HSV is given by the equations:

$$H = \begin{cases} 60 \frac{(G - B)}{M - m}, & \text{if } M = R \\ 60 \frac{(B - R)}{M - m} + 120, & \text{if } M = G \\ 60 \frac{(R - G)}{M - m} + 240, & \text{if } M = B \end{cases} \quad (3.12)$$

$$S = \begin{cases} \frac{(M - m)}{M}, & \text{if } M \neq 0 \\ 0, & \text{otherwise} \end{cases}$$

$$V = M$$

where $m = \min(R, G, B)$ and $M = \max(R, G, B)$. The luminance V and saturation S are normalized between 0 and 1. The H hue ranges from 0 to 360 degrees.

Similarly to HSV, the Hue, Saturation and Lightness (HSL) model is a three-dimensional representation and is formed by two cones of height 1, whose bases are coincident (Pedrini and Schwartz, 2008).

The hue is determined by the points in the circle of the common bases to the cones. The saturation varies from 0 to 1, depending on the distance to the axis of the cone. The lightness is along the vertical axis common to the two cones and varies in the scale [0, 1], where 0 means black and 1, white (Pedrini and Schwartz, 2008).

The conversion of the RGB space to HSL is given by the equations:

$$H = \begin{cases} 60 \frac{(G - B)}{M - m}, & \text{if } M = R \\ 60 \frac{(B - R)}{M - m} + 120, & \text{if } M = G \\ 60 \frac{(R - G)}{M - m} + 240, & \text{if } M = B \end{cases}$$

$$S = \begin{cases} \frac{(M - m)}{M + m}, & \text{if } 0 < L \leq 0,5 \\ \frac{(M - m)}{2 - (M + m)}, & \text{if } L > 0,5 \\ 0, & \text{if } M = m \end{cases} \quad (3.13)$$

$$L = \frac{M + m}{2}$$

where $m = \min(R, G, B)$ and $M = \max(R, G, B)$. The lightness L and saturation S are normalized between 0 and 1. Note that the transformation of the H component is the same as that used in the conversion of the RGB to HSV space in Eq. 3.12 and varies between 0 and 360 degrees.

All the color models of this family have the property of thinking of lighter colors, obtained by increasing the brightness or lightness, and darker colors, by the diminution of the same values. The intermediate colors are produced by decreasing the saturation (Pedrini and Schwartz, 2008).

Chapter 4

Proposed solution

A state of the art skin detection method has been recently developed by Brancati *et al.* (2017). Here, we review the method and extend it adding more rules to enforce the constraints and seeking for a better accuracy in terms of false positive rate without hurting the performance of the original method. Basically, we reversed the original hypothesis to create a new method. We combined both to strengthen it. A third variation with neighborhood approach is also provided.

In the case of the neighborhood approach, we also made additional implementations in order to clean up an undesired behavior on the output images that we called *diagonal effect*. In addition, we provide an implementation of a grid search to figure out the best combination of parameters to compute the trapezoids coordinates.

4.1 Original method

In order to describe the proposed extensions, we will first transcribe the original method that is based on the definition of image-specific trapezoids, named T_{YCb} and T_{YCr} , in the YCb and YCr subspaces, respectively. The trapezoids are essential to verify a relation between the chrominance components Cb and Cr in these subspaces (Brancati *et al.*, 2017).

The base of the trapezoids T_{YCr} and T_{YCb} (Fig. 4.1) are given by (Y_{min}, Cr_{min}) and (Y_{min}, Cb_{max}) in the YCr and YCb subspaces, respectively. The values $Cr_{min} = 133$, $Cb_{max} = 128$ were selected according to Chai and Ngan (1999) where a skin color map was designed using a histogram approach based on a given set of training images. Chai and Ngan observed that the Cr and Cb distributions of skin color falls in the ranges [133, 173] and [77, 127], respectively, regardless the skin color variation in different races.

The Cr_{max} parameter is calculated dynamically, taking into account the histogram of the pixels with Cr values in the range $[Cr_{min}, 183]$, looking for the maximum value of Cr associated with at least 0.1%¹ of pixels in the image. The same applies to Cb_{min} , taking the histogram with Cb values in the range $[77, Cb_{max}]$. Y_0 and Y_1 (shorter base of the upper trapezoid) are, respectively, the 5th and 95th percentile of the luminance values associated with the pixels of the image with $Cr = Cr_{max}$. A similar procedure is used to find the values of the shorter base of the other trapezoid, Y_2 and Y_3 (see Fig. 4.2 for an example).

The correlation rules between the chrominance components P_{Cr} and P_{Cb} of a pixel P are defined as:

- the minimum difference between the values P_{Cr} and P_{Cb} , denoted I_P ;
- an estimated value of P_{Cb} , namely P_{Cb_s} ;
- the maximum distance between the points (P_Y, P_{Cb}) and (P_Y, P_{Cb_s}) , denoted J_P .

¹In Brancati *et al.* (2017) this rate is reported to be equal to 10%. However, in the distributed source code we found the value 0.1%, that we are using in the experiments.

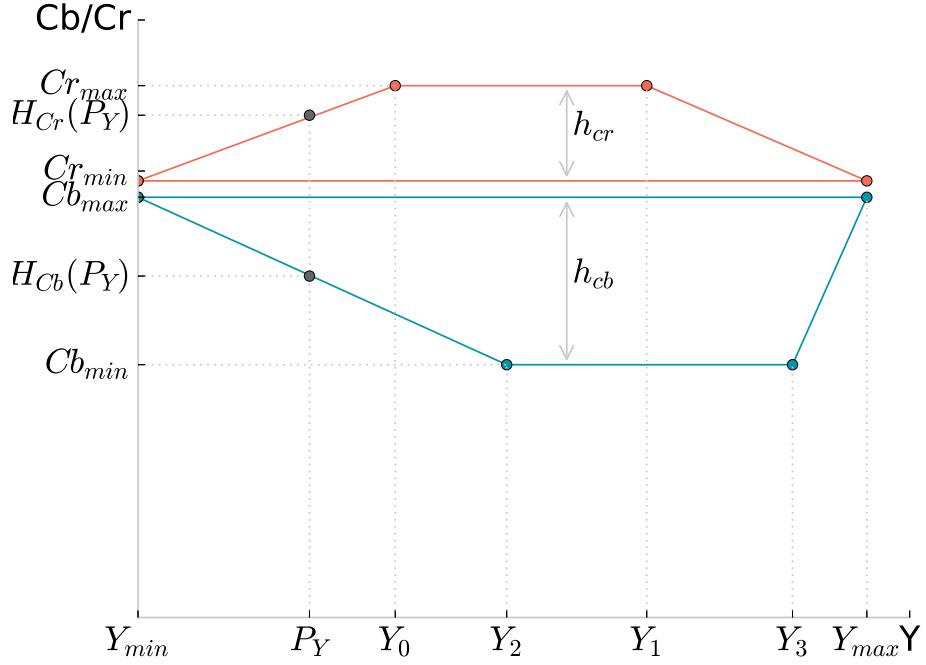


Figure 4.1: Graphical representation of the trapezoids as well as the parameters $Y_{min} = 0$, $Y_{max} = 255$, Y_0 , Y_1 , Y_2 , Y_3 , Cr_{min} , Cr_{max} , Cb_{min} , Cb_{max} , h_{Cr} , h_{Cb} , $H_{Cr}(P_Y)$, $H_{Cb}(P_Y)$. Source: adapted from (Brancale et al., 2017).

Therefore, to determine if P is skin, the following equations must hold:

$$P_{Cr} - P_{Cb} \geq I_P \quad (4.1)$$

$$|P_{Cb} - P_{Cb_s}| \leq J_P \quad (4.2)$$

The estimated value P_{Cb_s} is given by ²:

$$P_{Cb_s} = Cb_{max} - dP_{Cb_s} \quad (4.3)$$

where ³:

$$dP_{Cb_s} = \alpha \cdot dP_{Cr} \quad (4.4)$$

$$dP_{Cr} = P_{Cr} - Cr_{min} \quad (4.5)$$

² dP_{Cb_s} is the distance between the points (P_Y, P_{Cb_s}) and (P_Y, Cb_{max}) in the YCb subspace, calculated on the basis of dP_{Cr} , observing the inversely proportional behavior of the components. α is the rate between the normalized heights of the trapezoids in relation to the P_Y value.

³ dP_{Cr} is the distance between (P_Y, P_{Cr}) and (P_Y, Cr_{min}) points in the YCr subspace.

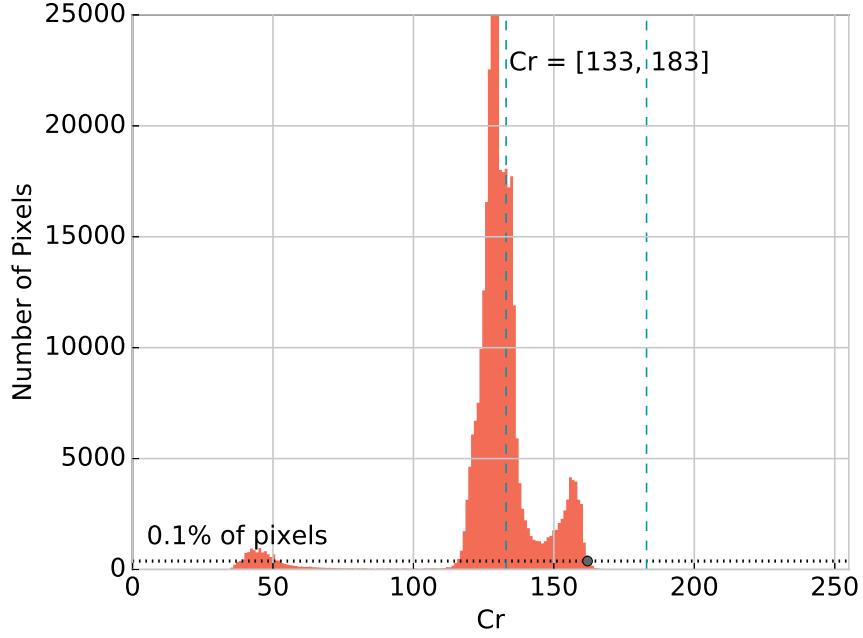


Figure 4.2: Computation of $Cr_{max} = 162$ based on Cr values histogram of a 724×526 image. Source: adapted from (Brancati et al., 2017).

The coordinates of the other sides of the trapezoids are given by $[P_Y, H_{Cr}(P_Y)]$ and $[P_Y, H_{Cb}(P_Y)]$, such that:

$$H_{Cr}(Y) = \begin{cases} Cr_{min} + h_{Cr} \left(\frac{Y - Y_{min}}{Y_0 - Y_{min}} \right) & Y \in [Y_{min}, Y_0] \\ Cr_{max} & Y \in [Y_0, Y_1] \\ Cr_{min} + h_{Cr} \left(\frac{Y - Y_{max}}{Y_1 - Y_{max}} \right) & Y \in [Y_1, Y_{max}] \end{cases} \quad (4.6)$$

$$H_{Cb}(Y) = \begin{cases} Cb_{min} + h_{Cb} \left(\frac{Y - Y_2}{Y_{min} - Y_2} \right) & Y \in [Y_{min}, Y_2] \\ Cb_{min} & Y \in [Y_2, Y_3] \\ Cb_{min} + h_{Cb} \left(\frac{Y - Y_3}{Y_{max} - Y_3} \right) & Y \in [Y_3, Y_{max}] \end{cases} \quad (4.7)$$

where $h_{Cr} = Cr_{max} - Cr_{min}$ and $h_{Cb} = Cb_{max} - Cb_{min}$, which are the heights of T_{YCr} and T_{YCb} , respectively.

The computation of those points are useful for the calculation of α . We first compute the distances $\Delta_{Cr}(P_Y)$ and $\Delta_{Cb}(P_Y)$ between the points $(P_Y, H_{Cr}(P_Y))$, $(P_Y, H_{Cb}(P_Y))$ and the base of the trapezoids:

$$\Delta_{Cr}(P_Y) = H_{Cr}(P_Y) - Cr_{min} \quad (4.8)$$

$$\Delta_{Cb}(P_Y) = Cb_{max} - H_{Cb}(P_Y) \quad (4.9)$$

Next, the distances are normalized with respect to the difference in size of the trapezoids:

$$\Delta'_{Cr}(P_Y) = \begin{cases} \Delta_{Cr}(P_Y) \cdot \frac{A_{T_{YCb}}}{A_{T_{YCr}}} & \text{if } A_{T_{YCr}} \geq A_{T_{YCb}} \\ \Delta_{Cr}(P_Y) & \text{otherwise} \end{cases} \quad (4.10)$$

$$\Delta'_{Cb}(P_Y) = \begin{cases} \Delta_{Cb}(P_Y) & \text{if } A_{T_{YCr}} \geq A_{T_{YCb}} \\ \Delta_{Cb}(P_Y) \cdot \frac{A_{T_{YCr}}}{A_{T_{YCb}}} & \text{otherwise} \end{cases} \quad (4.11)$$

where $A_{T_{YCr}}$ and $A_{T_{YCb}}$ are the areas of trapezoid T_{YCr} and T_{YCb} , respectively.

Then, the value of α is given by:

$$\alpha = \frac{\Delta'_{Cb}(P_Y)}{\Delta'_{Cr}(P_Y)} \quad (4.12)$$

Finally, I_P and J_P are given by:

$$I_P = sf \cdot [(\Delta'_{Cr}(P_Y) - dP_{Cr}) + (\Delta'_{Cb}(P_Y) - dP_{Cb_s})] \quad (4.13)$$

$$J_P = dP_{Cb_s} \cdot \frac{dP_{Cb_s} + dP_{Cr}}{\Delta'_{Cb}(P_Y) + \Delta'_{Cr}(P_Y)} \quad (4.14)$$

where:

$$sf = \frac{\min((Y_1 - Y_0), (Y_3 - Y_2))}{\max((Y_1 - Y_0), (Y_3 - Y_2))} \quad (4.15)$$

4.2 Extended method

The hypothesis defined in the original method is based on rules that an estimated value of the point P_{Cb} , namely P_{Cb_s} , must hold in order for the correlation to be valid. On the basis of the inversely proportional behavior of the chrominance components, we will rewrite the correlation rules with respect to the P_{Cr} point.

Thus, we have to refactor the correlation rules to put them in terms of the estimated value of P_{Cr} , that we denote as P_{Cr_s} ⁴:

$$P_{Cr_s} = dP_{Cr_s} + Cr_{min} \quad (4.16)$$

where⁵:

$$dP_{Cr_s} = \alpha \cdot dP_{Cr} \quad (4.17)$$

$$dP_{Cr} = Cb_{max} - P_{Cb} \quad (4.18)$$

Next, the constraints given by I_P and J_P in the Eq. 4.13 and 4.14 respectively, can be redefined as:

$$I'_P = sf \cdot [(\Delta'_{Cr}(P_Y) - dP_{Cr_s}) + (\Delta'_{Cb}(P_Y) - dP_{Cb})] \quad (4.19)$$

$$J'_P = dP_{Cr_s} \cdot \frac{dP_{Cr_s} + dP_{Cr}}{\Delta'_{Cb}(P_Y) + \Delta'_{Cr}(P_Y)} \quad (4.20)$$

Therefore, to determine if the pixel P is skin, we have to modify the conditions given by Eq. 4.1 and 4.2:

$$P_{Cr} - P_{Cb} \geq I'_P \quad (4.21)$$

$$|P_{Cr} - P_{Cr_s}| \leq J'_P \quad (4.22)$$

Doing this simple extension, we are now able to apply the method to the same sets of images to evaluate, in fact, the inversely proportional behavior of the chrominance components. More than that, we can combine all these constraints, given by the pair equations 4.1 and 4.2, 4.21 and 4.22, to reinforce the firstly defined hypothesis.

⁴ dP_{Cr_s} is the distance between the points (P_Y, P_{Cr_s}) and (P_Y, Cr_{min}) in the YCr subspace, calculated on the basis of dP_{Cr} , observing the inversely proportional behavior of the components. α is the rate between the normalized heights of the trapezoids in relation to the P_Y value.

⁵ dP_{Cr} is the distance between (P_Y, P_{Cr}) and (P_Y, Cb_{max}) points in the YCb subspace.

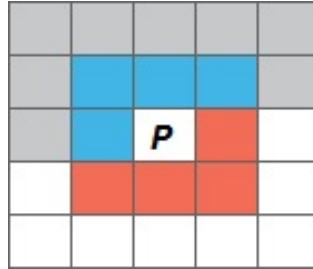


Figure 4.3: Neighbors evaluation with respect to P . If the image is scanned in raster order, $N_8^-(P)$ is the set of points that can be reached before P in an 8-neighbors window. Source: proposed by the author.

4.3 Neighborhood extended method

Both methods presented in sections 4.1 and 4.2 can be applied to detect skin pixels, either separated or in a conjunction rule. However, skin pixels do not usually appear isolated and we can improve the method using neighbor pixels information, when evaluating a pixel P , in order to decide if P represents human skin, or not. Let $N_8^-(P)$ the 8-neighbors of P that can be reached before P when scanning the image in raster order (blue points in Fig. 4.3).

Thus, we classify P as skin in the following manner: if the constraints given by the pair of equations 4.1 and 4.2, as well as 4.21 and 4.22 hold, then P is classified as skin. When only one of the conditions is satisfied, then we check the decision in $N_8^-(P)$. If three or more pixels are skin, then P will also be classified as a skin pixel. Figure 4.4 shows a flowchart of the aforementioned procedure described.

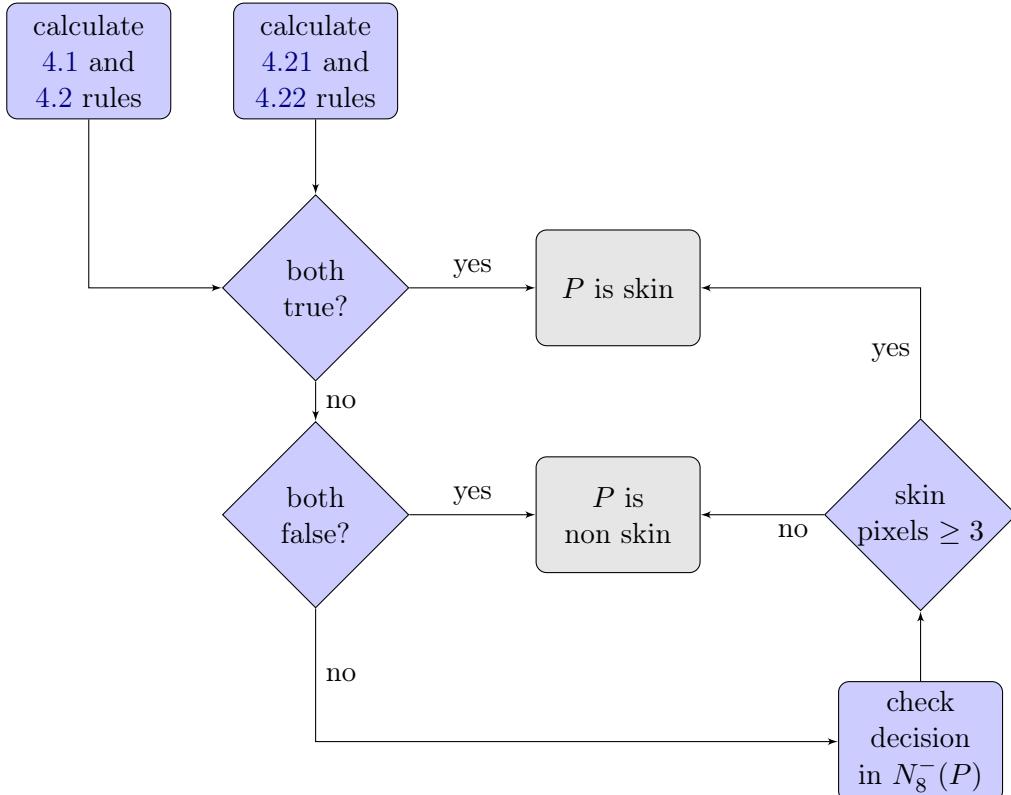


Figure 4.4: Flowchart of our proposed neighbors method. In **both false** decision, the **no** path means that one of the rules is true and we are in doubt if P is skin or not – here is where the neighbors are used to find out the label of P . Source: proposed by the author.

4.4 Supplementary neighborhood operations

The given neighborhood method presented in section 4.3 will end up with an undesired behavior on the output images that we called *diagonal effect* (see Fig. 4.5). This is caused due the shape of the window being used. Once we look only for the four already seen pixels of the *8-neighbors* window, the operation is so based in a non-symmetry mask. Ideally, we should look for all the eight neighbors of the pixel P being evaluated.

However, this particular implementation can add extra computational time and hurt the performance of the method. In addition, besides being a visually undesirable effect, the *diagonal effect* phenomenon causes us to have an increase in the false positive rate.

Therefore, we created an adaptation of the neighborhood method shown in 4.3. In this version, we basically scan the image, with a size of $W \times H$, in the raster order, and apply the original and reverse rules for every single pixel. We keep the result in a matrix of the same size ($W \times H$) of the input image. For each coordinate of this output matrix, we will have a two positions vector with the result of the original and reverse rules answer for this pixel. Next, we read each position of this output matrix and apply the *8-neighbors* operations in four different ways:

- (1) we look in the rules answer performing an AND. In other words, if both original and reverse rules are saying this pixel is skin, then we classify it as skin;
- (2) we look in the rules answer performing an OR. In other words, if one of the rules (original or reverse) is saying this pixel is skin, then we classify it as skin;
- (3) we look in the neighbors only querying the original (P_{Cb_s}) rules;
- (4) we look in the neighbors only querying the reversed (P_{Cr_s}) rules.

Of course, this variation will add some additional computational cost once we will scan the image one more time. This implementation can be enhanced, but the idea here is to only explore better the connectivity of the *8-neighbors* window and check, on the basis of a symmetric mask window, if the *diagonal effect* is gone as well as the measures are improved. Some experiments can be seen further in section 5.4.

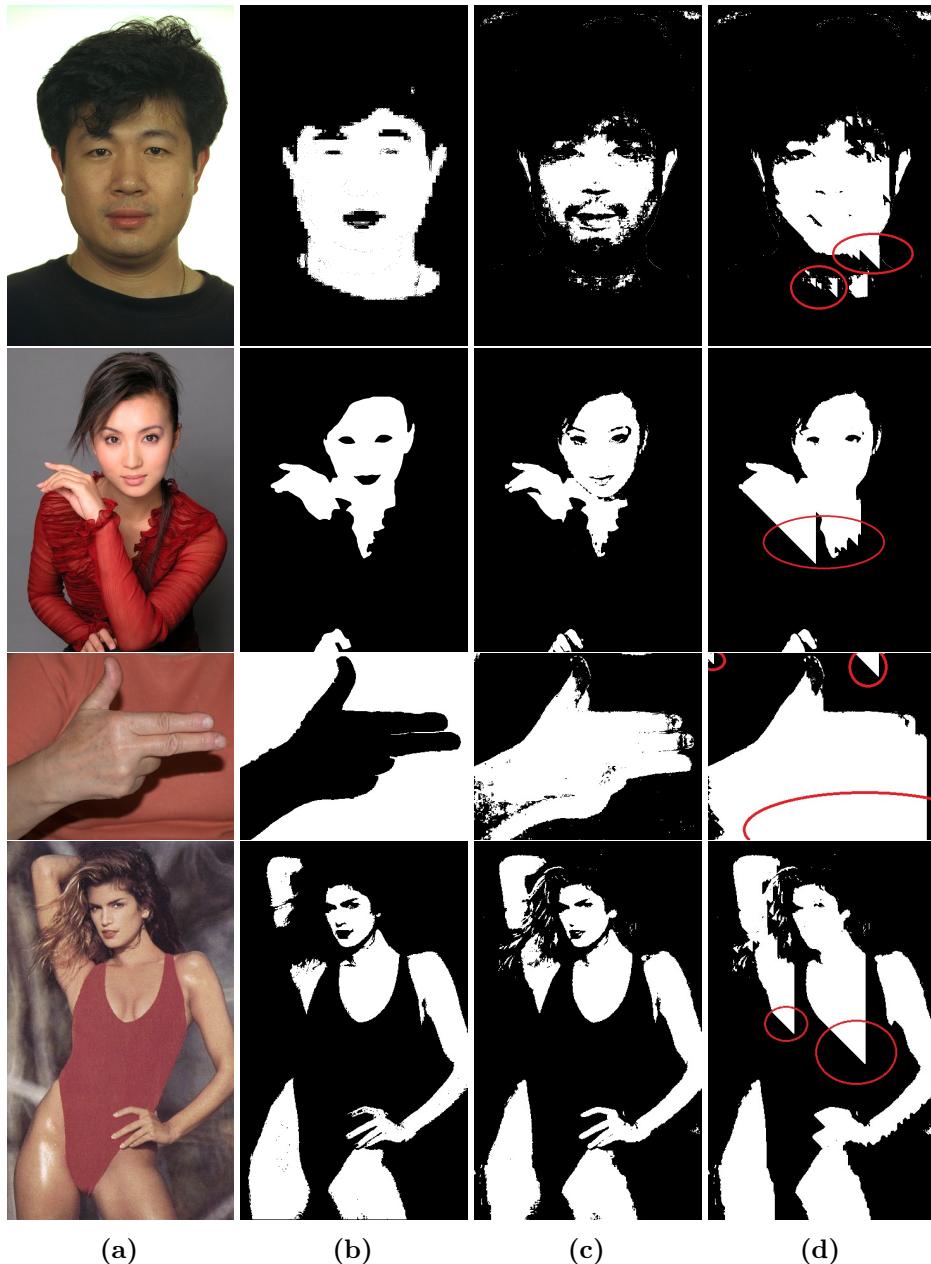


Figure 4.5: Image samples with the diagonal effect after the neighbors method segmentation. Each image is from (top-down) SFA, Pratheepan, HGR, and Compaq datasets, respectively, where: (a) original image (b) ground truth (c) combined method (f) neighbors method. Independently of the classification accuracy, we can clearly see the diagonal effect present in the output of the neighbors method segmentation in comparison with combined. Besides being a visually undesirable effect, this phenomenon causes us to have an increase in the false positive rate.

4.5 Trapezoids parameters tuning with a grid search strategy

As we could see on previous sections, this model is based on the definition of trapezoids to fit the skin color pixels distribution from a given image. According to Brancati *et al.* (2017), the coordinates of each trapezoid within the YCr and YCb sub-spaces are calculated based on the Y luminance component values. Y_0 and Y_1 are those used to define the shorter side of the upper trapezoid, and Y_2 and Y_3 the points used to define the shorter side of the lower trapezoid.

Y_0 and Y_1 are, respectively, the 5th and 95th percentile of the luminance values associated with the pixels of the image with $Cr = Cr_{max}$ (see Fig. 4.2 for an example). Similarly, Y_2 and Y_3 are, respectively, the 5th and 95th percentile of the luminance values associated with the pixels of the image with $Cb = Cb_{min}$.

To the best of our knowledge, there is any justification to choose the 5th and 95th percentile to be the right parameters to define the trapezoids coordinates. For this reason, we decided to shot different combination of these parameters to figure out which pair better works for the model fitting. In addition, we would like to answer the question: why 5th and 95th percentile have been used?

Thus, we used a well-known technique called grid search to find the best range combination from a hyper-parameter space. By constructing the model in this manner, we can leverage the classification results by finding the optimized parameters' combination, if other different from the ones defined earlier by Brancati *et al.* (2017). Despite we do not exhaustively consider all parameter combinations, we used an efficient search strategy by sampling a given number of candidates. For each chosen parameters candidate, we dynamically used them in the combined method⁶ to test every single image of each dataset described in section 5.1. Lastly, we sort the results table using respectively, *F-measure*, *Precision*, and *Recall* metrics, as detailed in section 5.2, and established a comparison to get optimized parameters. The algorithm TRAPEZOIDS-PARAMETERS-GRID-SEARCH(*dataset*) shows how the grid search have been performed.

```

TRAPEZOIDS-PARAMETERS-GRID-SEARCH(dataset)
1    $P_{min} = 5$ 
2   Results = []
3
4   while  $P_{min} \leq 95$ 
5        $P_{max} = P_{min}$ 
6       while  $P_{max} \leq 95$ 
7           SET-COMBINED-METHOD-Y-PARAMETERS( $P_{min}, P_{max}$ )
8           SEGMENT-DATASET-IMAGES(dataset)
9           Precision, Recall, Fmeasure = COMPUTE-METRICS(dataset)
10          PUSH(Results,  $P_{min}, P_{max}, Precision, Recall, Fmeasure$ )
11
12           $P_{max} = P_{max} + 5$ 
13           $P_{min} = P_{min} + 5$ 
14
15  SORT-BY(Results, Fmeasure, Precision, Recall)
16  return Results
```

⁶In fact, we could apply this approach in any of the described methods, but once the trapezoids definition do not change among them, we think that employing it only in combined method is sufficient for the parameters optimization.

In short, TRAPEZOIDS-PARAMETERS-GRID-SEARCH(*dataset*) will trigger combinations of P_{min} and P_{max} ⁷ percentiles in the range [5, 95] with a step of 5. In line 7, the parameters are changed in the combined method and applied further in 8 to classify each image within the dataset. Next, the metrics are computed on every single image in line 9 by comparing the output with the ground truth. The resulting metrics are pushed into *Results* matrix in line 10. We keep an average of overall images classified in each dataset. Finally, we sort the results matrix according the criteria aforementioned in the end of the procedure.

Detailed output of this experiments and analysis can be seen in chapter 5, specifically in section 5.5, where an examination of the behavior of the most performing parameters is given as well as others which did not succeed.

⁷ P_{min} is the minimum percentile index of the *Y* luminance values. P_{max} is the maximum percentile index of the *Y* luminance values.

Chapter 5

Evaluation

In this chapter we present some experimental evaluations of the proposed extensions along with the original method in four widely known datasets: SFA, Pratheepan, HGR, and Compaq. In addition, a brief definition of the evaluation metrics used is shown for the sake of clarity. We also provide some results of the supplementary neighborhood adaptation that we built to remove the *diagonal effect* as well as to explore different neighbors techniques. Finally, we show the grid search parameters experiments results with aim of trapezoids parameters tuning. All the experiments are analyzed and discussed in each section separately.

5.1 Datasets

Datasets are an integral part of the field of computer vision. In the particular case of computer vision, datasets consist, primarily, of images or videos for tasks such as object detection, motion tracking, segmentation, and classification. In general, they are constructed with tens, hundreds, or even thousands of images in different environments, distinct illumination conditions, various quality and resolution, and many other aspects.

We gathered four widely known datasets, SFA, Pratheepan, HGR, and Compaq, which will be briefly introduced in next sections, to be used in our experiments. Together, they sum up 7,423 images in different size and resolution, and more than 1.5 billion pixels tested in all the experiments, counting only the original images.

5.1.1 UCI

Named UCI in this work, this dataset was proposed by [Bhatt and Dhall \(2012\)](#) and obtained from the machine learning repository of the University of California in Irvine ([Lichman, 2013](#)). The dataset consists of pixel samples of images of various skin and non-skin textures obtained from thousands of arbitrary faces images of different ages, gender, and races ([Minear and Park, 2004](#); [Phillips et al., 1996](#)).

The UCI contains 245,057 samples, composed of 3 attributes that constitute the input vector $x = [x_1, x_2, x_3]$, $x \in \mathbb{R}^d$, where d is the space dimension which represents, respectively, blue (B), green (G) and red (R) channels of the RGB color model. In addition, a fourth column determines the class to which the sample x belongs, denoted by y , where $y \in Y$ and $Y = \{+1, -1\}$. In other words, each sample is an RGB pixel with a given label.

The Table 5.1 exemplifies a short excerpt from the UCI database. It is worth mentioning that 194,198 out of the 245,057 are non-skin pixels and 50,859 pixels with different skin tones. In addition, the images that were used to extract the dataset were not made available by the authors.

| B | G | R | Label |
|-----|-----|-----|-------|
| 74 | 85 | 123 | 1 |
| 207 | 215 | 255 | 1 |
| 74 | 82 | 122 | 1 |
| 202 | 211 | 255 | 1 |
| 54 | 72 | 125 | 1 |
| ... | ... | ... | ... |
| 166 | 164 | 116 | -1 |
| 148 | 150 | 91 | -1 |
| 29 | 26 | 5 | -1 |
| 167 | 166 | 115 | -1 |
| 180 | 177 | 133 | -1 |

Table 5.1: Excerpt with samples from the UCI dataset. Each of the first three columns represents a pixel channel of the RGB color space ranging from 0 to 255. The fourth column is the label assigned to the sample, which can assume +1 if it is skin and -1, otherwise. Originally, the class representing a non-skin pixel had value 2, replaced by -1 for compliance with the experiments.

Since the data are points in the RGB space, it is possible to plot it for a better interpretation of them, as shown in the Figure 5.1.

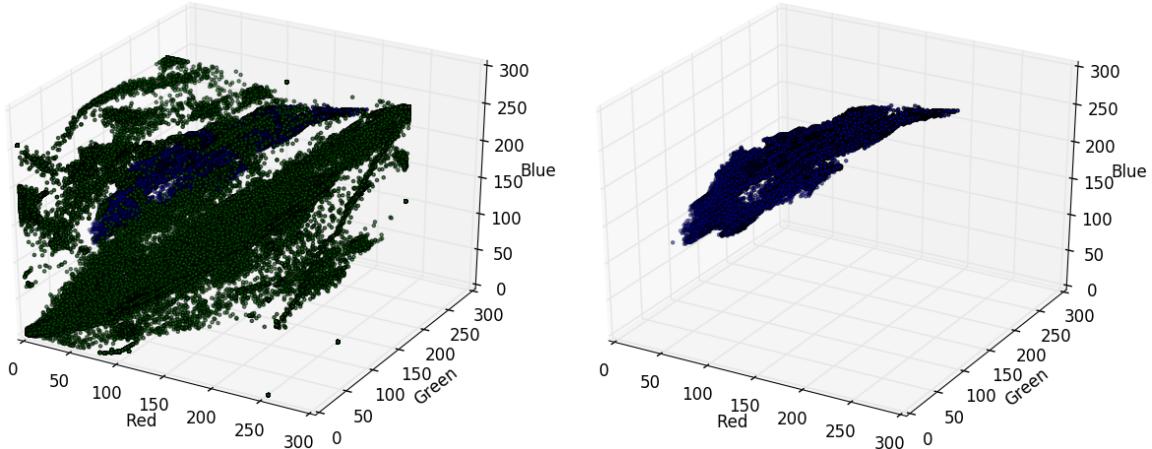


Figure 5.1: 3-dimensional view of the RGB channels of the UCI dataset. The blue points are skin samples and the green ones are non-skin. On the left are all samples of the dataset; to the right only the skin samples. Source: proposed by the author.

5.1.2 SFA

SFA, the name of the dataset proposed by Casati *et al.* (2013), stands for Skin of FERET and AR Database. The SFA is a set of images of frontal faces obtained from two other color image databases: the FERET, created by Phillips *et al.* (1996), and the AR proposed by Martínez and Benavente (1998), which provided 876 and 242 images each, respectively. It is important to notice that AR images have a white background and small variations of skin color. In other words, the environment is more controlled than the images in FERET (Casati *et al.*, 2013). Figure 5.3 shows some of the 1,118 samples available.

Casati *et al.* (2013) also extracted different window patches of each skin and non-skin samples to facilitate future research. The samples were randomly generated considering the ground truth mask ¹ of each image, being three samples of skin and five of non-skin. Each sample is a window of size $n \times n$, where n is odd, with a central pixel, from which other sample sizes have been created, ranging from 1×1 to 35×35 , as can be seen in Figure 5.2.

¹Ground truth is the term used to denote an image whose point of interest is properly segmented and highlighted, discarding the remaining pixels giving them uniform colors.

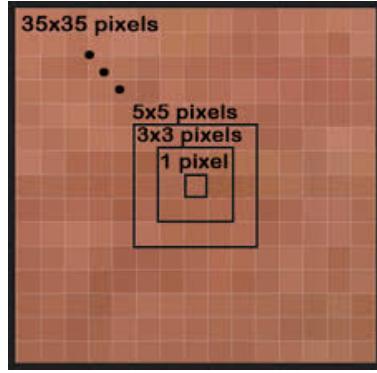


Figure 5.2: Structure of the windows that form the SFA patch samples. In total, there are 3,354 skin samples and 5,590 non-skin samples for each window size. Source: Casati et al. (2013).

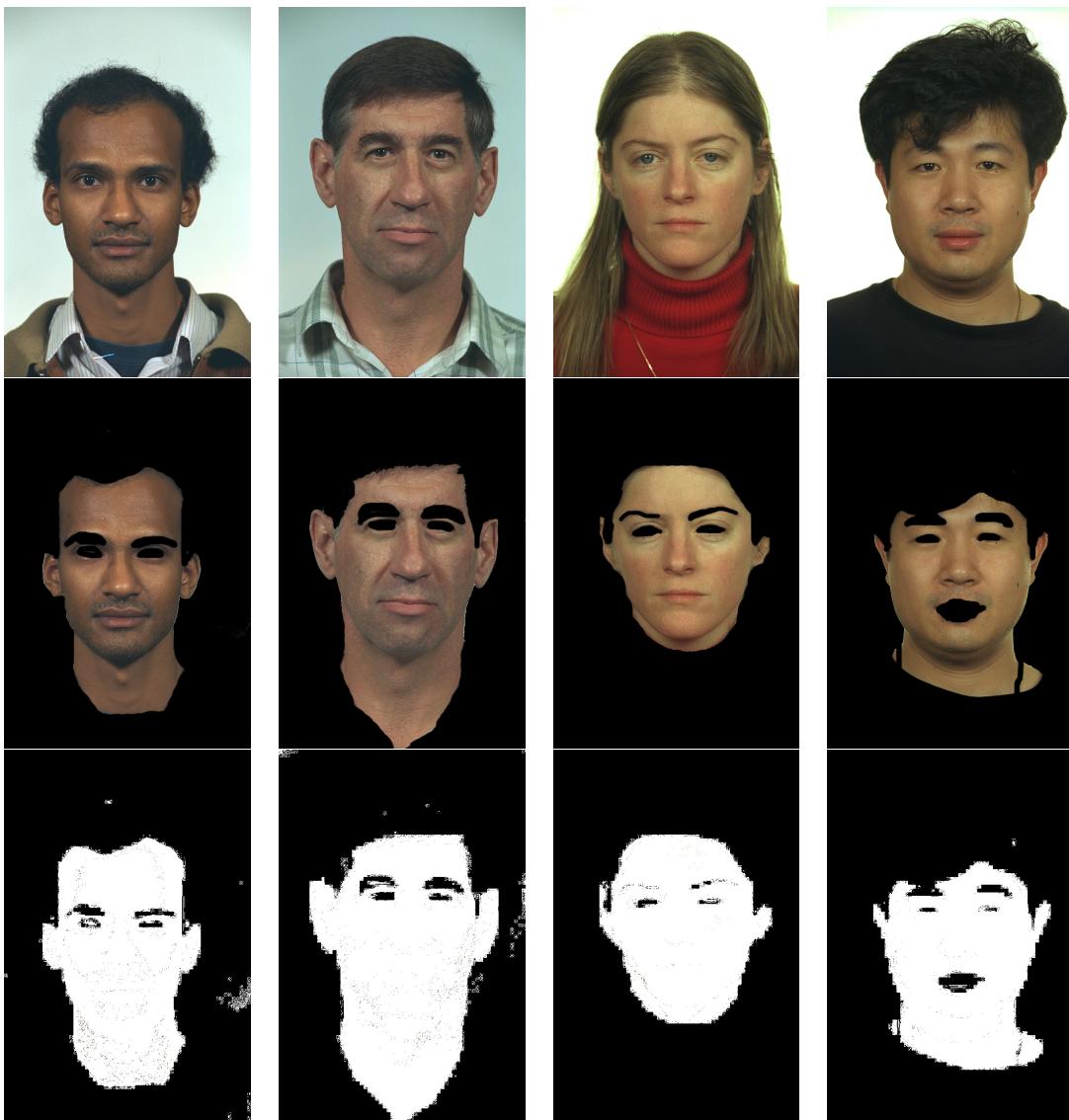


Figure 5.3: Examples of SFA face image database. First row are the original images and the second contain the colored ground truth with the skin color pixels annotated manually. The black color $RGB = (0, 0, 0)$ was assigned to all pixels in the background. In the third row we have the binary ground truth images. We generated these samples based on the colored ground truth, by creating a mask, assigning $(255, 255, 255)$ for the pixels which were not background $(0, 0, 0)$. One can see some noise in the results, but the samples were enough for further experiments. In addition, the original images were not perfectly annotated. Therefore, some salt noise can be seen in non-skin regions. Source: Casati et al. (2013).

It is worth mentioning that we do not use these patches in our experiments. Once the methods tested in this work only depends on the input image itself. Therefore, we can simply ignore these sampling patches during experiments. However, one could use them to evaluate the ability of the methods in terms of false detection rate, once the patches are made available for skin and non-skin labeled images separately.

5.1.3 Pratheepan

The images in the Pratheepan dataset were downloaded randomly from Google for human skin detection research. There are 78 images of family and face captured with a range of distinct cameras using different color enhancement and under different illumination conditions [Tan et al. \(2012\)](#). Figure 5.4 shows some of the 78 samples available.



Figure 5.4: Examples of Pratheepan skin dataset. At the top row is the original image, and at the bottom row the ground truth with the skin color pixels annotated. Here, the ground truth are binary images, where the black color $RGB = (0, 0, 0)$ was assigned to all pixels in the background. Source: [Tan et al. \(2012\)](#).

5.1.4 HGR

The database for Hand Gesture Recognition (HGR) contains the gestures from Polish and American Sign Language. There are 1,558 images acquired in different conditions of background, dimensions and lightening. In addition to original and ground truth binary skin mask images, it includes hand feature points location in separate files. Figure 5.5 shows some of the 1,558 samples available ([Grzejszczak et al., 2016](#); [Kawulok et al., 2014](#); [Nalepa and Kawulok, 2014](#)).

The images within it were acquired in three different series. A set of 899 was captured in uncontrolled background and lighting. A small set of 85 was obtained in gray (44) and uncontrolled (41) background; the lighting was uniform. The third group contains 574 images in controlled background (green tone), using uniform lighting conditions ([Grzejszczak et al., 2016](#); [Kawulok et al., 2014](#); [Nalepa and Kawulok, 2014](#)).



Figure 5.5: Examples of HGR skin dataset. At the top row is the original image and at the bottom row the ground truth with the skin color pixels annotated. Differently from Pratheepan and SFA, the ground truth is also binary images, but the black color $RGB = (0, 0, 0)$ was assigned to all pixels when they represent skin patches – and we take this in consideration during experiments. Source: Grzejszczak et al. (2016); Kawulok et al. (2014); Nalepa and Kawulok (2014).

5.1.5 Compaq

Compaq can be considered as the first large skin dataset and, probably is the most used for skin detection classifiers. It consists of 13,635 images crawled from the internet, which 4,670 contain skin regions and another subset of 8,965 images not containing any skin. The ground truth images are poorly annotated on the basis of an automatic software tool (Mahmoodi and Sayedi, 2016).

It is worth mentioning that this database is no longer available and we had obtained a copy of it by contacting the authors. We also had to fix some few images due lack of ground truth or files corrupted. The final amount of images with skin used in the experiments is 4,669. Figure 5.6 shows some of the 4,669 images with skin samples available used in the experiments (Jones and Rehg, 2002).

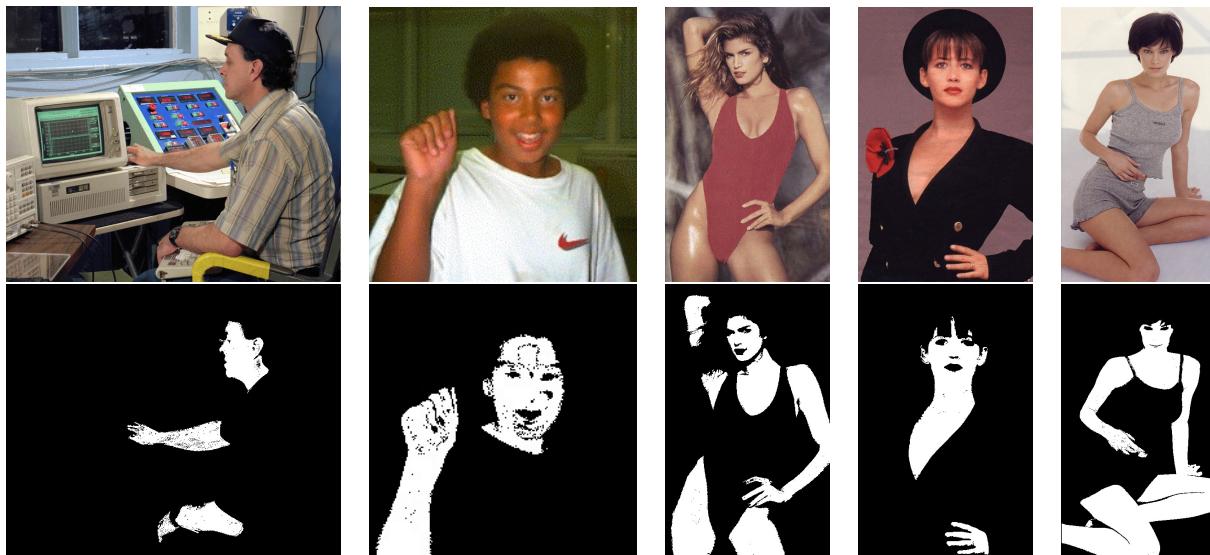


Figure 5.6: Examples of Compaq skin/non-skin dataset. At the top row is the original image, and at the bottom the ground truth with the skin color pixels annotated. Here, the ground truth are binary images, where the black color $RGB = (0, 0, 0)$ was assigned to all pixels in the background. Source: Jones and Rehg (2002).

5.2 Evaluation measures

Precision, *Recall*, *Specificity* and *F-measure* have been used as evaluation metrics. They are the same used in [Branca et al. \(2017\)](#) to compare the performance with state-of-the-art methods. They are also widely used by the scientific community. These metrics are given by the following formulas:

$$\text{Precision} = \frac{TP}{TP + FP}$$

$$\text{Recall} = \frac{TP}{TP + FN}$$

$$\text{Specificity} = \frac{TN}{TN + FP}$$

$$F - \text{measure} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

where TP, TN, FP, FN are, respectively, the number of true positive, true negative, false positive, and false negative pixels counted in the image, which are obtained from the confusion matrix (see Table 5.2).

| | | prediction outcome | |
|--------------|----------|--------------------|----------------|
| | | skin | non-skin |
| ground truth | skin | True Positive | False Negative |
| | non-skin | False Positive | True Negative |

Table 5.2: Confusion matrix table used to count the number of true positive, true negative, false positive, and false negative pixels in the image during experiments. These numbers are fundamental input for evaluation measures.

5.3 Rule-based experiments

In this section we present some experimental evaluations of the proposed extensions described in sections 4.2 and 4.3, as well as the original method in four widely known datasets: SFA, Pratheepan, HGR and Compaq. The latest three of them have also been used in [Branca et al. \(2017\)](#).

Table 5.3 shows quantitative result metrics of the experiments. Column 1 refers to the dataset used. Column 2 refers to the method being experimented: Original for the original hypothesis; Reverse refers to the reverse hypothesis with respect to P_{Cr_s} parameter; Combined refers to the combination of both of the former methods (see Sec. 4.2); Neighbors refers to the extension of the method using the neighborhood approach (see Sec. 4.3).

The original method was compared with six well known rule-based methods in literature using four different datasets, three of them, HGR, Pratheepan and Compaq, we have also been used here. We applied the methods against a fourth dataset (SFA) to increase and strengthen the different number of samples tested.

Because the method had the best *F-measure* in the HGR and Pratheepan datasets in comparison

| Dataset | Hypothesis | Precision | Recall | Specificity | F-measure |
|------------|------------|---------------|---------------|---------------|---------------|
| Compaq | Original | 0.4354 | 0.8046 | 0.8046 | 0.5650 |
| | Reverse | 0.3971 | 0.7232 | 0.7921 | 0.5127 |
| | Combined | 0.4906 | 0.6251 | 0.8856 | 0.5498 |
| | Neighbors | 0.4708 | 0.7421 | 0.8463 | 0.5761 |
| Pratheepan | Original | 0.5513 | 0.8199 | 0.8230 | 0.6592 |
| | Reverse | 0.5249 | 0.7326 | 0.8188 | 0.6116 |
| | Combined | 0.6681 | 0.6683 | 0.9164 | 0.6682 |
| | Neighbors | 0.6280 | 0.7515 | 0.8871 | 0.6843 |
| HGR | Original | 0.8938 | 0.7664 | 0.9274 | 0.8252 |
| | Reverse | 0.7929 | 0.8429 | 0.8337 | 0.8171 |
| | Combined | 0.8994 | 0.6952 | 0.9390 | 0.7843 |
| | Neighbors | 0.8818 | 0.7935 | 0.9211 | 0.8353 |
| SFA | Original | 0.8636 | 0.4214 | 0.9692 | 0.5664 |
| | Reverse | 0.8563 | 0.7730 | 0.9381 | 0.8125 |
| | Combined | 0.9288 | 0.3958 | 0.9894 | 0.5551 |
| | Neighbors | 0.9176 | 0.5111 | 0.9826 | 0.6565 |

Table 5.3: Quantitative result metrics of the proposed enhancements and Brancati *et al.* (2017). For each dataset, we have four different applications: the original hypothesis with respect to P_{Cb_s} , the reverse hypothesis with respect to P_{Cr_s} , the one which combines both, and the extension using the neighborhood approach.

with the other six methods and, in addition, because it performed the top first *Precision* in HGR and second in Pratheepan, we decided to compare the proposed extensions only to the original method.

As one can see in Table 5.3, the reverse hypothesis performed better than the original method and achieved the best *Recall* in HGR and SFA. It also achieved the best *F-measure* in SFA with a 0.8125 rate, which gave almost 0.25 in gain compared to the original.

It is important to note that, the significant improvement of the *Recall* in HGR and SFA datasets is, probably, due to the nature of the images that form each of them. HGR and SFA contain images where we have a great concentration of skin pixels – hands and arms in the case of HGR, and faces in the case of SFA occupying a considerable region of the image. Furthermore, a large part of them were collected in controlled environments, on the background and lighting conditions point of view. Thus, this behavior must be taken into consideration when selecting the method to apply within an application, since this can be decisive for a potentially performance improvement.

In general, the reverse method increased the *Recall* but did not perform well in *Precision* and *Specificity* measures. When we combined both methods, the best *Precision* and *Specificity* were achieved for all datasets but it loses some performance in *Recall*. However, it still has very good *F-measure* rates.

The neighborhood approach achieved the best *F-measure* in Compaq, HGR, and Pratheepan. Moreover, the other metrics still are in a very high rate for all datasets, being in the top second in almost all cases. If we compare the neighbors approach with the original, except for the *Recall* – where we only got the best result in SFA –, we can see that our implementation achieved the best measures practically for all other metrics, in the four datasets.

Therefore, the combined and neighbors approaches are very competitive compared to the original method. Furthermore, all the variations of the original method are still computed in quadratic time, maintaining the desired computational efficiency that are useful in different application domains, mainly near real time systems (processing time of about 10ms for a typical image of dimensions 300x400).

Figures 5.7, 5.8, 5.9 and 5.10, present some qualitative results with image samples in column (a) along with the results for each method tested. Column (b) presents the respective ground truth for each image in column (a), column (c) presents the original method Brancati *et al.* (2017) results,

column (d) presents the respective reverse method results, column (e), the combined method results and column (f) the extended neighborhood method.

Qualitatively, we can see that, in general, the reverse method removes a large part of the reddish pixels from the background of the image (e.g. see the third image in the Figure 5.7, first and fourth images in the Figure 5.8, second image in Figure 5.9, and third image in Figure 5.10), which the original method was not able to. On the other hand, the reverse method has not been successful in taking off yellowish-toned background regions (e.g. see the third image in Figure 5.9, and fifth image in Figure 5.10).

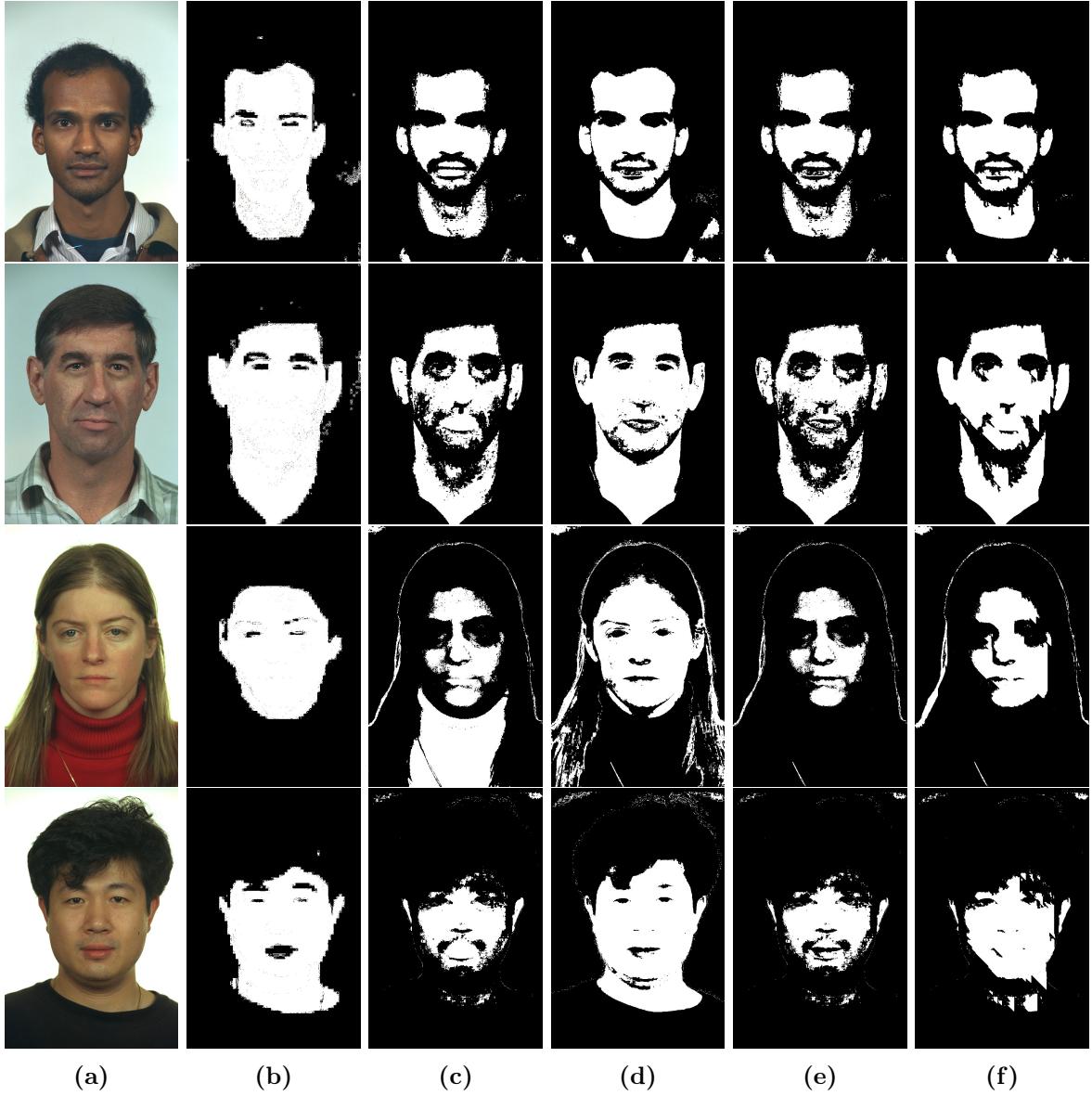


Figure 5.7: Image samples with the results of each method in SFA dataset: (a) original image (b) ground truth (c) original method [Brancati et al. \(2017\)](#) (d) reverse method (e) combined method (f) neighbors method.

However, when we blend the original method along with the reverse in the method we call combined, both background regions of reddish and yellowish pixels are almost completely removed. In addition, salt-like noises are also dropped, since the rules together are more rigid (e.g. see column (e) combined method for the third image in Figure 5.9, and fifth image in Figure 5.10). Obviously, this causes an undesired effect of removing some of the skin pixels of which we are interested. This helps us understand why the recall decreases with the application of the combined rule.

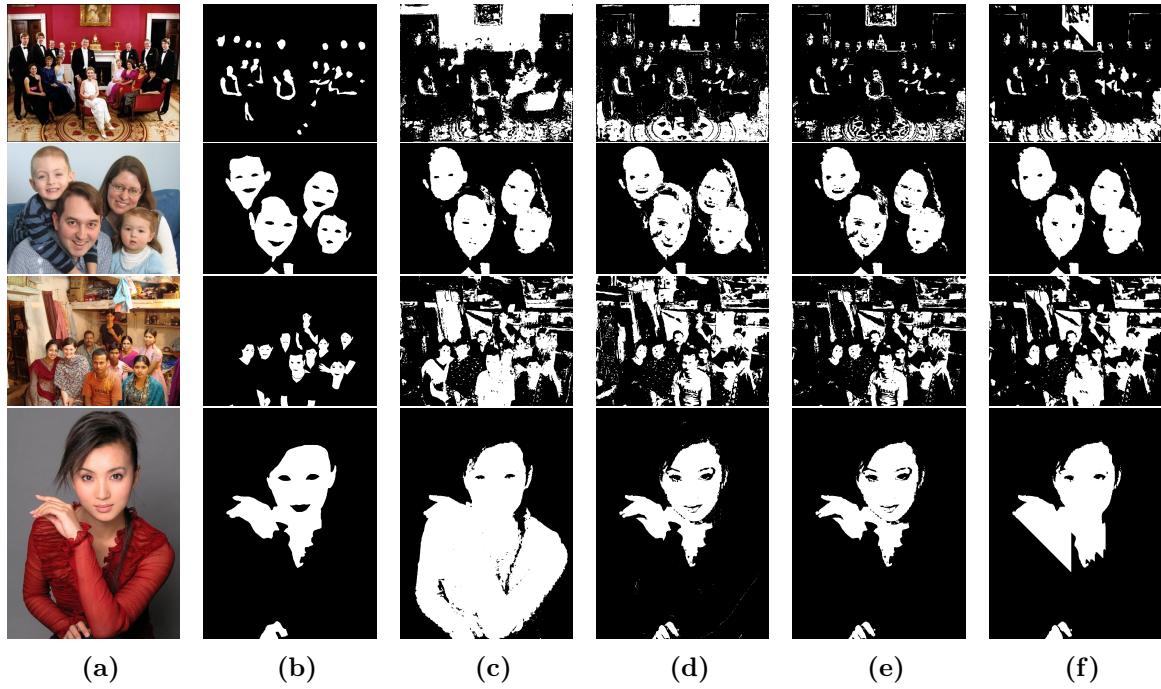


Figure 5.8: Image samples with the results of each method in Pratheepan dataset: (a) original image (b) ground truth (c) original method Brancati et al. (2017) (d) reverse method (e) combined method (f) neighbors method.

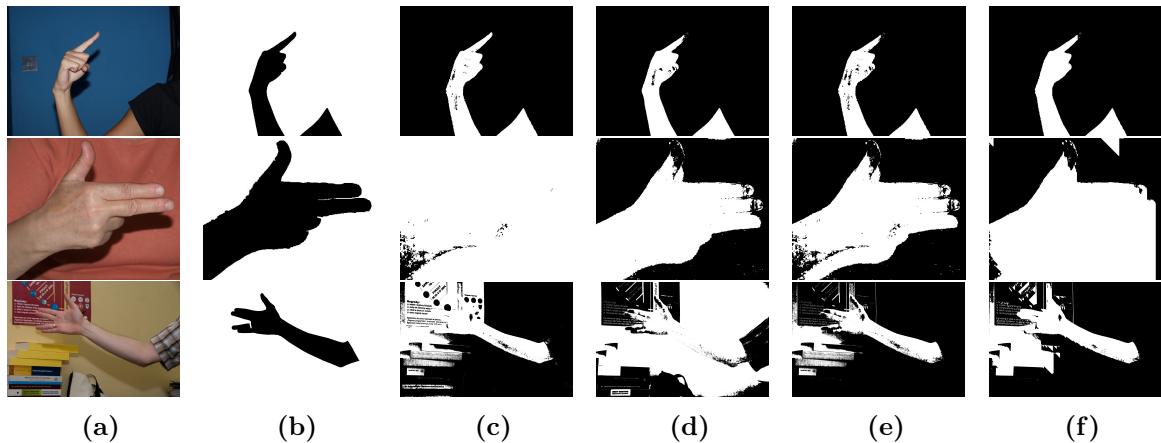


Figure 5.9: Image samples with the results of each method in HGR dataset: (a) original image (b) ground truth (c) original method Brancati et al. (2017) (d) reverse method (e) combined method (f) neighbors method.



Figure 5.10: Image samples with the results of each method in Compaq dataset: (a) original image (b) ground truth (c) original method Brancati et al. (2017) (d) reverse method (e) combined method (f) neighbors method.

5.4 Supplementary neighborhood operations experiments

In this section we will show some experimental results of the supplementary neighborhood adaptation described in section 4.4. In short, we basically scan the image, with a size of $W \times H$, in the raster order, and apply the original and reverse rules for every single pixel. We keep the result in a matrix of the same size ($W \times H$) of the input image. For each coordinate of this output matrix, we will have a two positions vector with the result of the original and reverse rules answer for this pixel. Finally, we count those answers in four different strategies. The results can be seen in table 5.4.

| Dataset | Hypothesis (Neighbors) | Precision | Recall | Specificity | F-measure |
|------------|------------------------|---------------|---------------|---------------|---------------|
| Compaq | AND | 0.5121 | 0.6252 | 0.8941 | 0.5630 |
| | OR | 0.3786 | 0.9037 | 0.7203 | 0.5336 |
| | P_{Cr_s} only | 0.4132 | 0.7254 | 0.8032 | 0.5265 |
| | P_{Cb_s} only | 0.4478 | 0.8053 | 0.8120 | 0.5755 |
| Pratheepan | AND | 0.6731 | 0.6789 | 0.9127 | 0.6760 |
| | OR | 0.4624 | 0.8837 | 0.7321 | 0.6072 |
| | P_{Cr_s} only | 0.5285 | 0.7414 | 0.8163 | 0.6171 |
| | P_{Cb_s} only | 0.5630 | 0.8218 | 0.8292 | 0.6682 |
| HGR | AND | 0.9007 | 0.7203 | 0.9378 | 0.8005 |
| | OR | 0.7978 | 0.9084 | 0.8238 | 0.8495 |
| | P_{Cr_s} only | 0.7937 | 0.8600 | 0.8331 | 0.8256 |
| | P_{Cb_s} only | 0.8818 | 0.7935 | 0.9211 | 0.8353 |
| SFA | AND | 0.9345 | 0.3947 | 0.9899 | 0.5549 |
| | OR | 0.8345 | 0.8181 | 0.9176 | 0.8262 |
| | P_{Cr_s} only | 0.8612 | 0.7922 | 0.9375 | 0.8252 |
| | P_{Cb_s} only | 0.8953 | 0.7690 | 0.9286 | 0.8273 |

Table 5.4: Quantitative result metrics of the proposed supplementary neighborhood adaptation. For each dataset, we have four different applications of the neighbors operations, respectively: applying an AND between the original and reverse rules, applying an OR between the original and reverse rules, considering the P_{Cr_s} (reverse) only, and considering the P_{Cb_s} (original) only.

It is worth mentioning that the goal here is to explore better the connectivity of the 8-neighbors window and check, on the basis of a symmetric mask window, if the *diagonal effect* is gone as well as the measures are improved. Therefore, we are not worried about the additional computational cost taken to scan the image one more time. Even though, this implementation can be enhanced by, for instance, keeping the latest three lines of the image scanned in memory to be verified by the 8-neighbors window backward to have a final decision when evaluating a pixel.

From the table 5.4 we can see that the application of the neighborhood approach using AND gives us the best precision and specificity in all datasets. On the other hand, we lost performance in the recall in relation to the others approaches. Speaking of recall, the loss is in the order of 20% up to 30% in the Compaq, Pratheepan and HGR datasets, and approximately 50% in the SFA.

Clearly there is a trade-off between increasing precision and decreasing recall and vice versa, just as in the experiments done in section 5.3 with all methods. When we use a more relaxed rule, as in the case of the OR or the isolated rules, we get a better recall, but there is also an abrupt drop in precision and specificity. Another side effect of this phenomenon is to increase the false positive rate.

The AND conjunction approach is most similar to that implemented in neighborhood extended method (see Sec. 4.3). The results obtained by that approach show low variability in relation to the adaptations shown in the experiments in this section. Therefore, for the sake of implementation, the approach given in the neighborhood implementation may be a good starting point. Nevertheless,

we can apply some other complementary technique, such as weights in the pixels, to measure those more or less relevant to the decision making in the neighborhood. This can potentially diminish the effect of this trade-off and obtain more harmonic measures while removing the undesired *diagonal effect*.

5.5 Grid search parameters experiments

In one part of this work we are concerned with understanding and, perhaps, improving the choice of parameters that define the trapezoids. They are a fundamental part of the model that segments the skin pixels in an image, the main role of the methods developed here. In short, as described in section 4.5, 5th and 95th percentiles of the histogram of Y luminance component have been used by Brancati *et al.* (2017) to be the right parameters to define the trapezoids coordinates. For this reason, we decided to shot different combination of these parameters to figure out which pair better works for the model fitting. In addition, we would like to answer the question: why 5th and 95th percentiles have been used?

Thus, we created a simple grid search algorithm (see details in section 4.5) to find the best range combination of those parameters. Despite we do not exhaustively consider all parameter combinations, we used an efficient search strategy by sampling a given number of candidates. For each chosen parameters candidate, we dynamically used them in the combined method to test every single image of each dataset described in section 5.1. Lastly, we sort the results table using respectively, *F-measure*, *Precision*, and *Recall* metrics. The results with these metrics, in that given order, for each dataset, can be seen in Appendix A.

It is worth mentioning that the grid search algorithm starts with P_{min} percentile index in 5 and P_{max} percentile lower bound is set to P_{min} in the inner loop. Thus, we will no longer have a combination of parameters such as [15, 10], that means, we always have combinations such that $P_{max} \geq P_{min}$. This will produce a table with results according the template given in Figure 5.11.

| | 5 | 10 | ... | 90 | 95 |
|----|---|----|-----|----|----|
| 5 | ■ | ■ | ■ | ■ | ■ |
| 10 | ■ | | | | |
| : | | | | | |
| 90 | | | | ■ | ■ |
| 95 | | | | ■ | ■ |

Figure 5.11: The output template table with result metrics of the grid search algorithm. P_{min} percentile index is in vertical axis and P_{max} percentile index is in horizontal axis. The highlighted cells – from the main diagonal and above – are the ones which will have values of the metrics after running the method for the given combination of parameters. Source: proposed by the author.

We performed this experiment in all four datasets: Compaq, Pratheepan, HGR, and SFA. For each dataset, respectively, we have a scatter plot of *F-measure*, *Precision*, and *Recall*, with their respective variance, which can be seen in Figures 5.12, 5.13, 5.14, and 5.15. Each chart is showing the resulting metrics, in y (vertical) axis², by using a fixed P_{min} and varying P_{max} along x (horizontal) axis. The shaded path of the measures are the variance and tell us how far we are from the mean when looking for each image within the dataset individually.

We can see predominantly that larger intervals – e.g. [5, 85], [5, 90], [5, 95] – resulted in the best *Precision* in all datasets. On the other hand, smaller intervals, with both P_{min} and P_{max} near the upper bound (95) – e.g. [80, 90], [85, 95], [90, 95] –, performed better in *Recall*. Thus, if we set up a

²We set the range in the charts to start at 0.25 for better visualization of the series.

specific pair of parameters for the percentile to compute the trapezoid coordinates, it can produce a good *Precision* but it may hurt the *Recall* and vice versa.

Therefore, evaluate *F-measure* in this situation seems to be the correct path, since it gives us a harmonic measure between *Precision* and *Recall*. That's why we sorted the results (see Tables A.1, A.2, A.3, and A.4 for details) using the order *F-measure*, *Precision*, and *Recall* as a criteria. Another important observation is the behavior of variance in each result, that means, even good measures with huge variance could be a problem for real world applications.

In Compaq, we can see that top *F-measure* results were obtained with pair of parameters such as $[5, 25], \dots, [5, 95]$, while keeping good measures in both *Precision* and *Recall*. A similar behavior can be seen in Pratheepan, but among the highest *F-measure* scores are those where $P_{min} = 10$. Next are those starting with $P_{min} = 5$. So, we could state that the values $[5, 95]$ chosen by Brancati *et al.* (2017) are fair enough since the results were quite good. Even so, the results are insignificantly worse than the highest ranked ones (see Table 5.5).

However, in HGR as well as in SFA top *F-measure* results were obtained with pair of parameters such that $P_{min} = P_{max}$. For instance, we can see in HGR results that *Recall* = 0.8641 and *F-measure* = 0.8667 when $P_{min} = 5$ and $P_{max} = 5$, while $[5, 95]$ interval resulted in *Recall* = 0.6952 and *F-measure* = 0.7843 – a gain in the order of 24% and 10% for each metric, respectively. A similar behavior can be seen in the results of SFA, where the gain in *Recall* and *F-measure* are in the order of 67% and 39% for each metric, respectively, which is a very huge difference. It is worth mentioning that, despite *Precision* and *Specificity* have a slightly decreasing, they are still around the Brancati *et al.* (2017) results.

| Dataset | P_{min} | P_{max} | Precision | Recall | Specificity | F-measure |
|------------|-----------|-----------|-----------|--------|-------------|-----------|
| Compaq | 5 | 95 | 0.4906 | 0.6251 | 0.8856 | 0.5498 |
| | 5 | 25 | 0.4819 | 0.6459 | 0.8762 | 0.5520 |
| | 5 | 35 | 0.4866 | 0.6374 | 0.8808 | 0.5519 |
| | 5 | 40 | 0.4877 | 0.6356 | 0.8818 | 0.5519 |
| | 5 | 30 | 0.4844 | 0.6408 | 0.8789 | 0.5517 |
| | 5 | 45 | 0.4884 | 0.6335 | 0.8827 | 0.5516 |
| Pratheepan | 5 | 95 | 0.6681 | 0.6683 | 0.9164 | 0.6682 |
| | 10 | 55 | 0.6560 | 0.6955 | 0.9055 | 0.6752 |
| | 10 | 80 | 0.6558 | 0.6950 | 0.9056 | 0.6748 |
| | 10 | 85 | 0.6557 | 0.6949 | 0.9056 | 0.6748 |
| | 10 | 95 | 0.6557 | 0.6950 | 0.9057 | 0.6747 |
| | 10 | 90 | 0.6556 | 0.6950 | 0.9056 | 0.6747 |
| HGR | 5 | 95 | 0.8994 | 0.6952 | 0.9390 | 0.7843 |
| | 5 | 5 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| | 10 | 10 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| | 15 | 15 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| | 20 | 20 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| | 25 | 25 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| SFA | 5 | 95 | 0.9288 | 0.3958 | 0.9894 | 0.5551 |
| | 5 | 5 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| | 10 | 10 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| | 15 | 15 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| | 20 | 20 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| | 25 | 25 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |

Table 5.5: Quantitative result metrics of the proposed grid search parameters tuning. For each dataset, we have different applications of the combined method with different pairs of P_{min} and P_{max} percentiles. The first line is the default one $[5, 95]$, as reported in the experiments given in Table 5.3. Next five lines are the top five results ordered by *F-measure*, *Precision*, and *Recall*, respectively.

On the basis of this scenario, we observed that when we have $P_{min} = P_{max}$, the resulting metric is absolute the same for any combination of equal percentile parameters. For instance, in Compaq dataset, when we tried $P_{min} = 5$ and $P_{max} = 5$, we got $Precision = 0.4172$, $Recall = 0.7333$, $Specificity = 0.8096$, and $F\text{-measure} = 0.5318$. The result is the same for $P_{min} = 10$ and $P_{max} = 10$ onward up to $P_{min} = 95$ and $P_{max} = 95$. This behavior will repeat for every single dataset tested.

Based on this result, we started to investigate the source code given in the original method by Brancati *et al.* (2017). We found out that, when the percentiles are the same, the computation of the parameters who define the trapezoids is impacted. In other words, Y_0 , Y_1 , Y_2 , Y_3 , Y_{min} , Y_{max} , Cr_{min} , Cb_{max} are always the same, i.e. assume default values. Even Cb_{min} , Cr_{max} , that are still computed dynamically by the internal method functions, do not change when P_{min} , P_{max} percentiles are changed, since they are dependent on the previous parameters and the histogram of the image itself that never change. The same behavior will be observed when $P_{min} > P_{max}$.

It is important to note that, in the case of Compaq and Pratheepan, where $P_{min} = P_{max}$, the results worsen significantly in terms of *Precision*. On the other hand, they have a significant gain in the HGR and SFA datasets.

This particular phenomenon occurs by the nature of the images that form each of these images databases. Both Compaq and Pratheepan contain images with more complex scenes, uncontrolled environment, distinct lighting conditions and, in general, images randomly collected from the internet. On the other hand, HGR and SFA contain images where we have a great concentration of skin pixels – hands and arms in the case of HGR, and faces in the case of SFA occupying a considerable region of the image. Furthermore, a large part of them were collected in controlled environments, on the background and lighting conditions point of view.

Therefore, this behavior must be taken into consideration when selecting a pair of P_{min} and P_{max} to apply in the method in question, since this can be decisive for a potentially performance improvement.

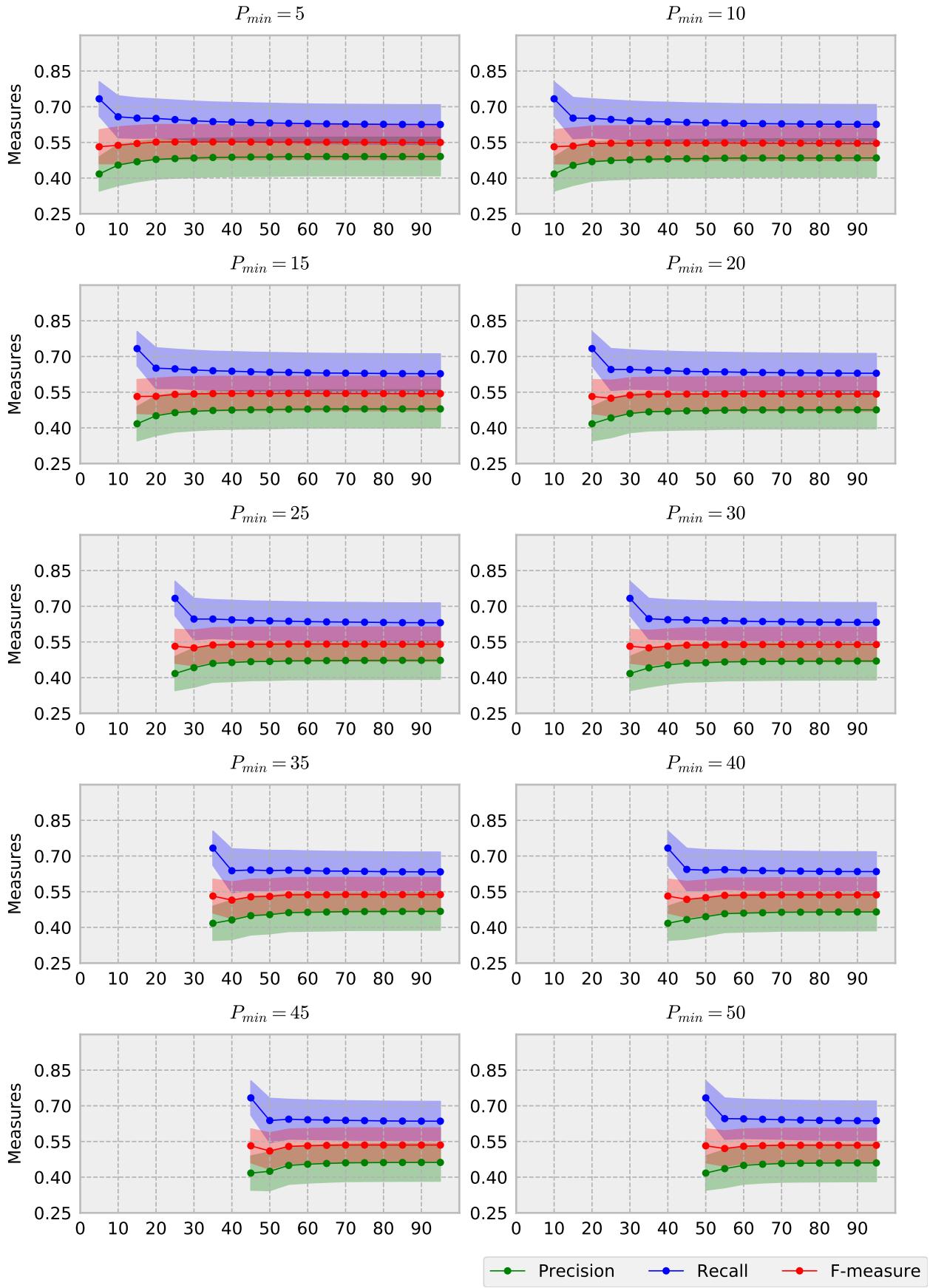


Figure 5.12: Scatter plot with the quality measures for grid search parameters in Compaq dataset.

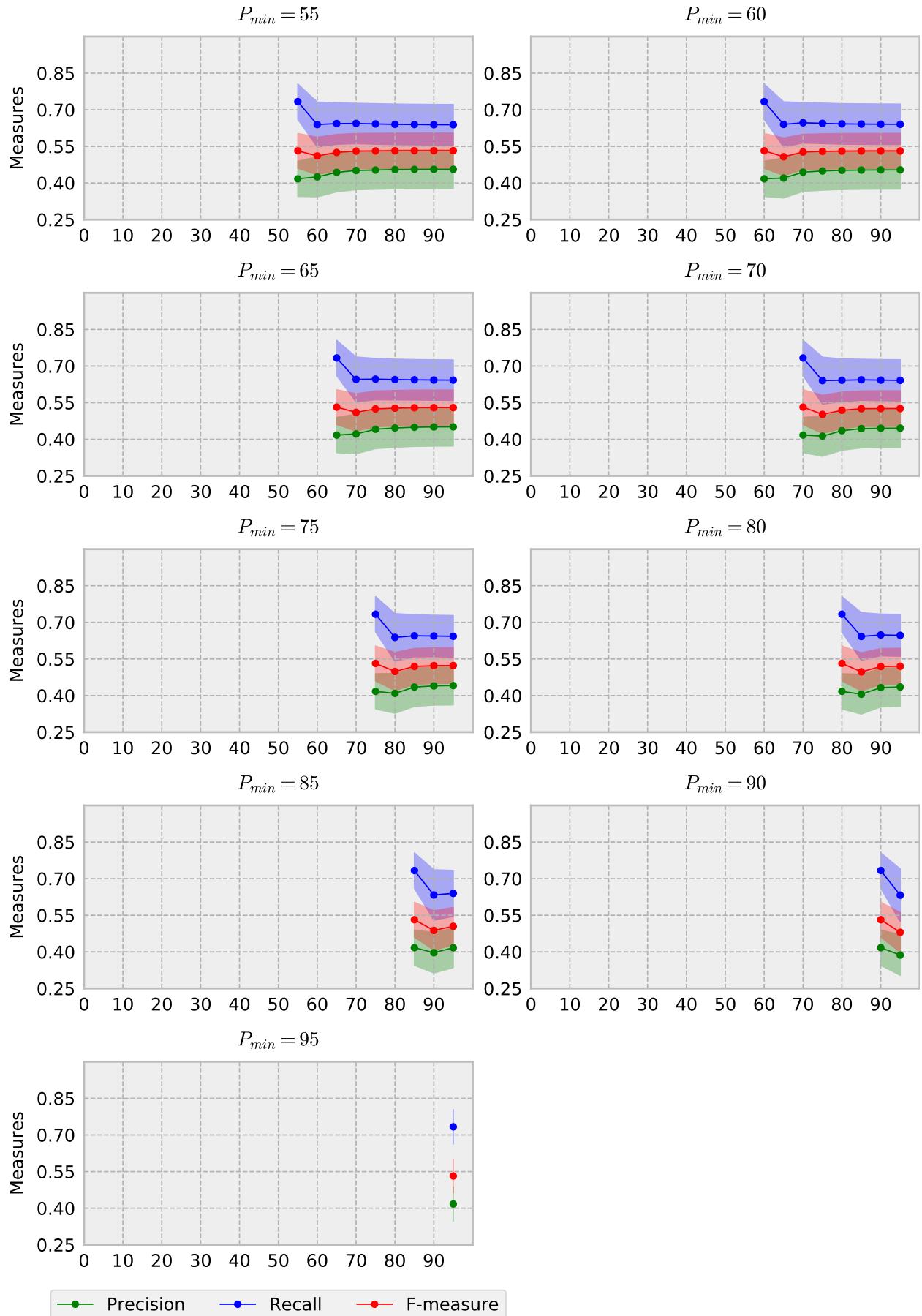


Figure 5.12: Scatter plot with the quality measures for grid search parameters in Compaq dataset (cont.).

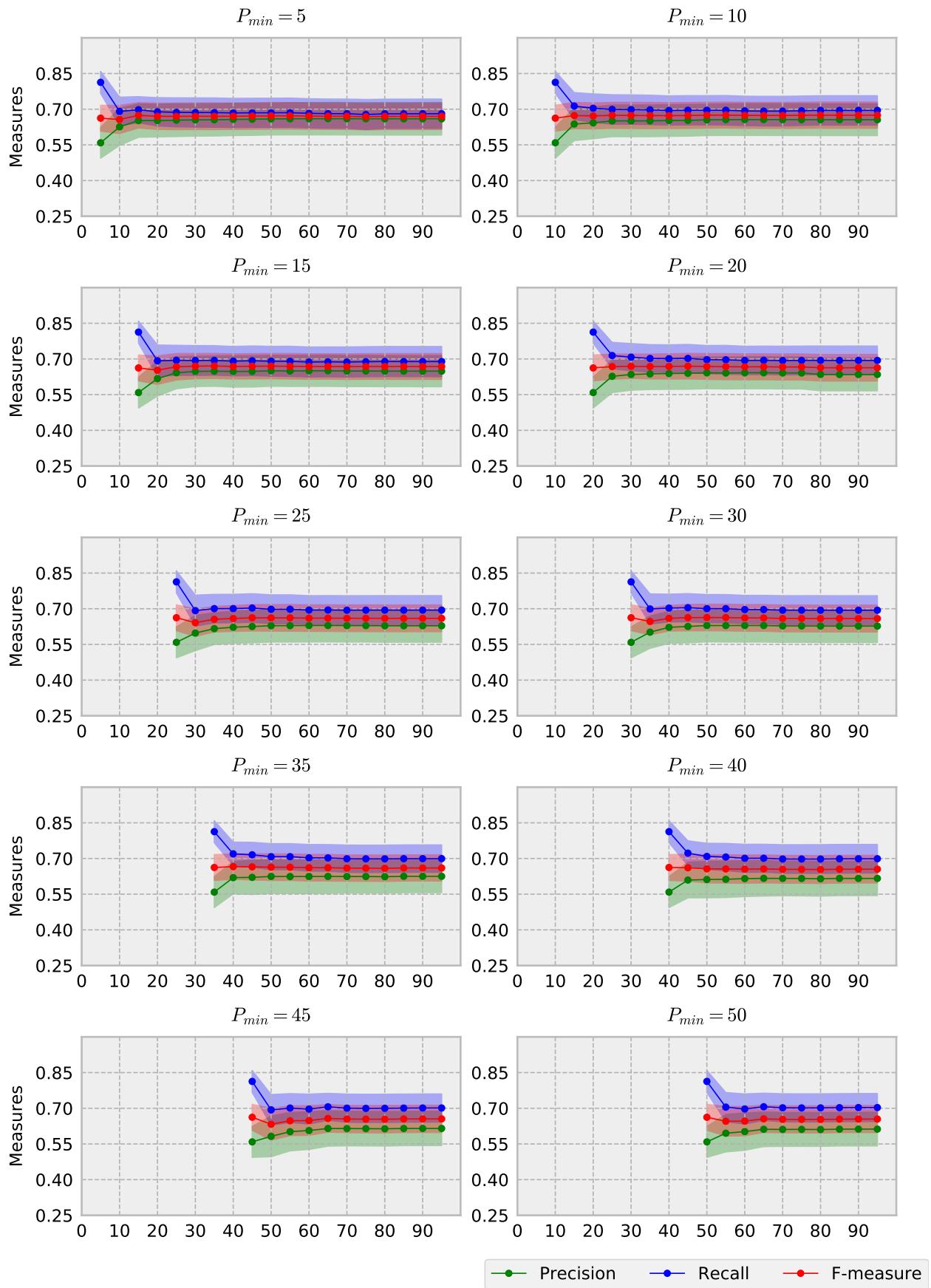


Figure 5.13: Scatter plot with the quality measures for grid search parameters in Pratheepan dataset.

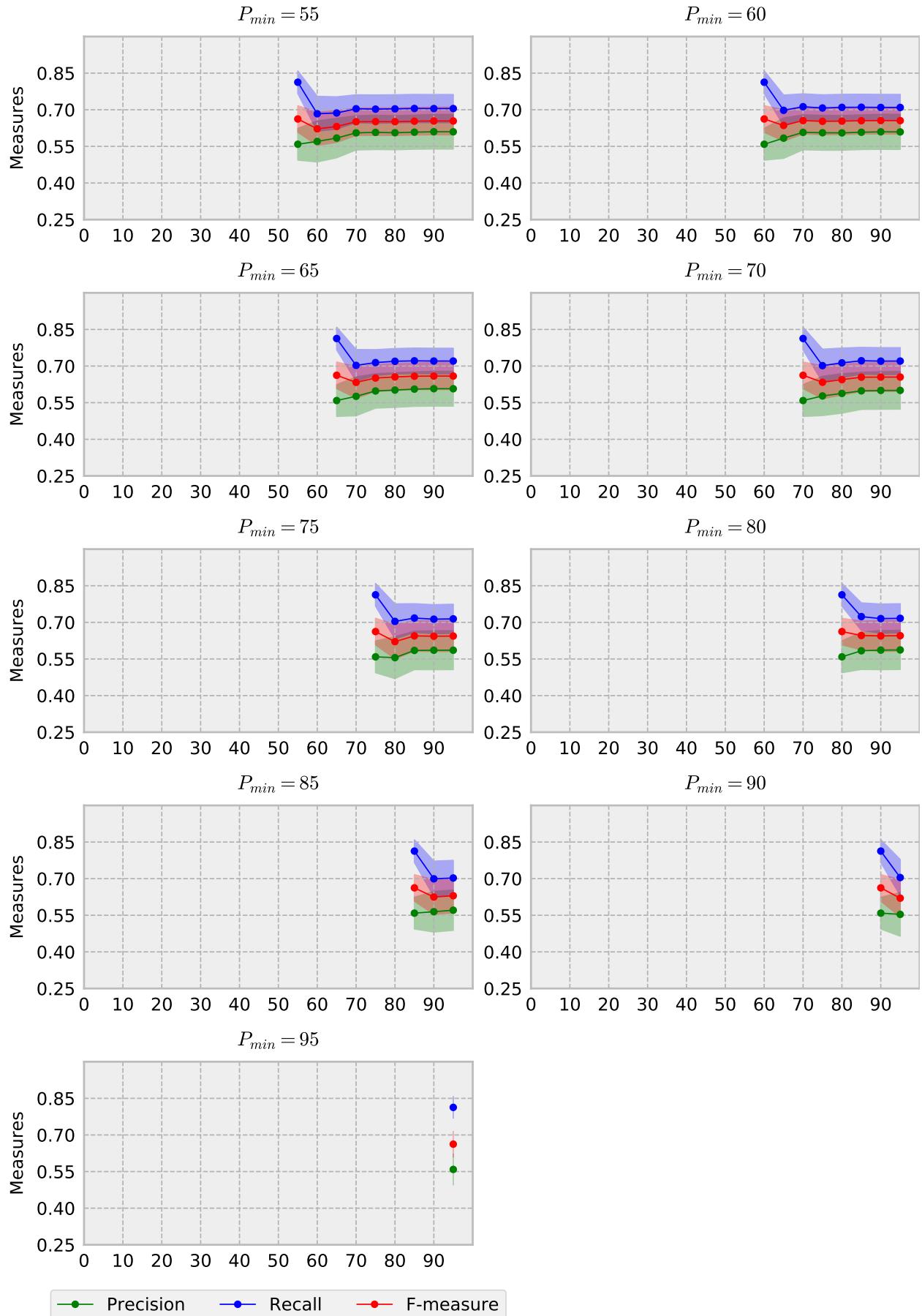


Figure 5.13: Scatter plot with the quality measures for grid search parameters in Pratheepan dataset (cont.).

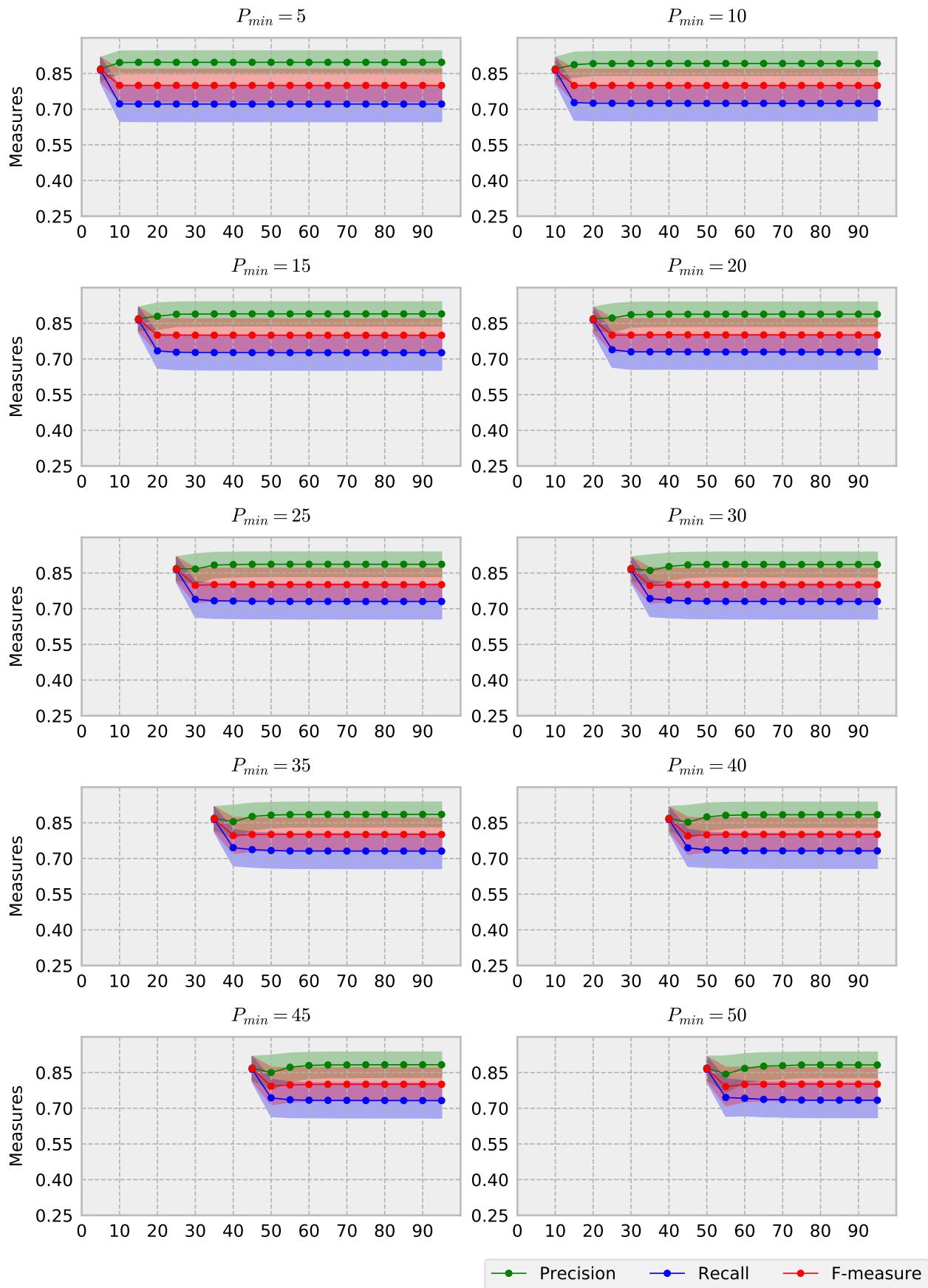


Figure 5.14: Scatter plot with the quality measures for grid search parameters in HGR dataset.

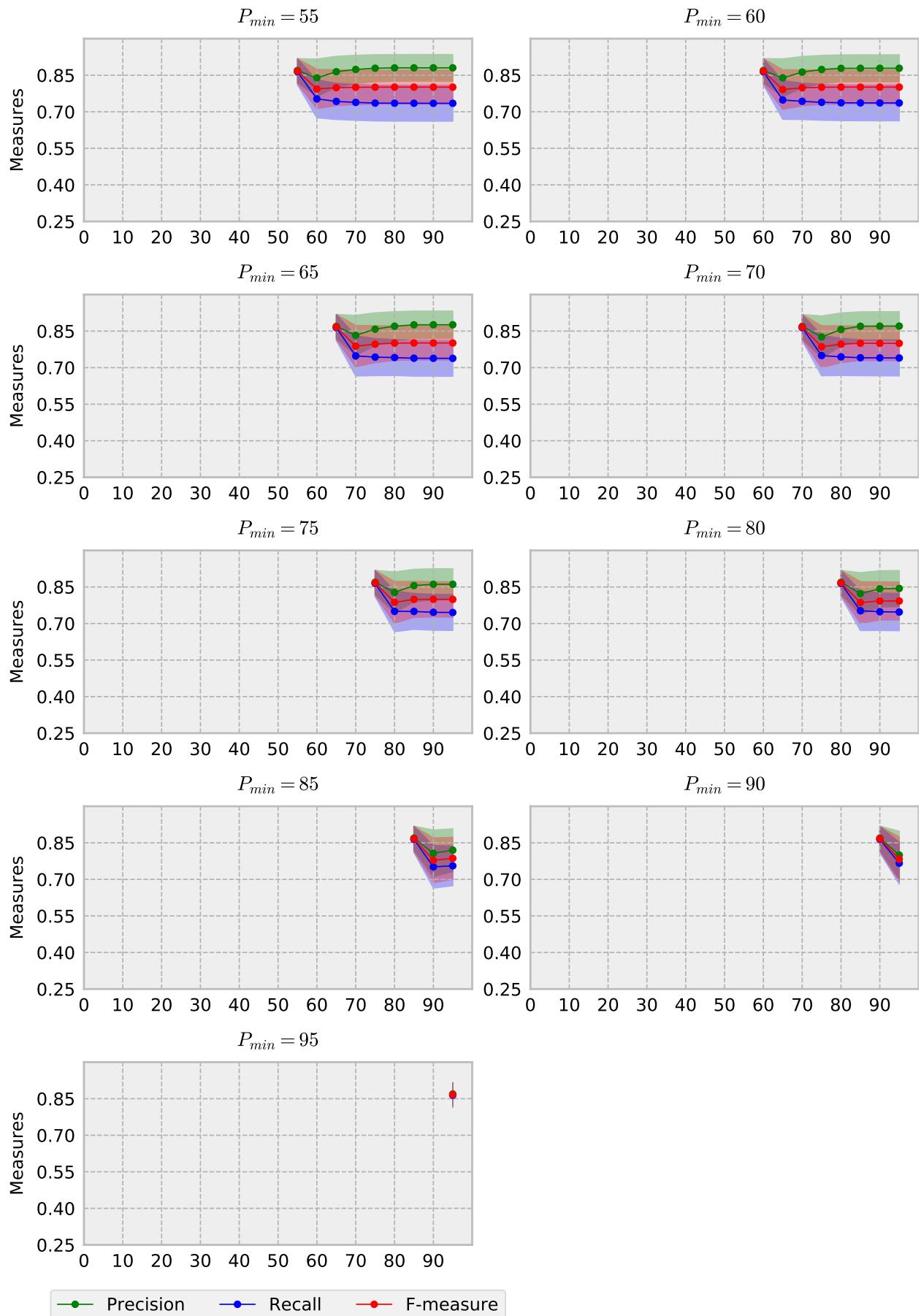


Figure 5.14: Scatter plot with the quality measures for grid search parameters in HGR dataset (cont.).

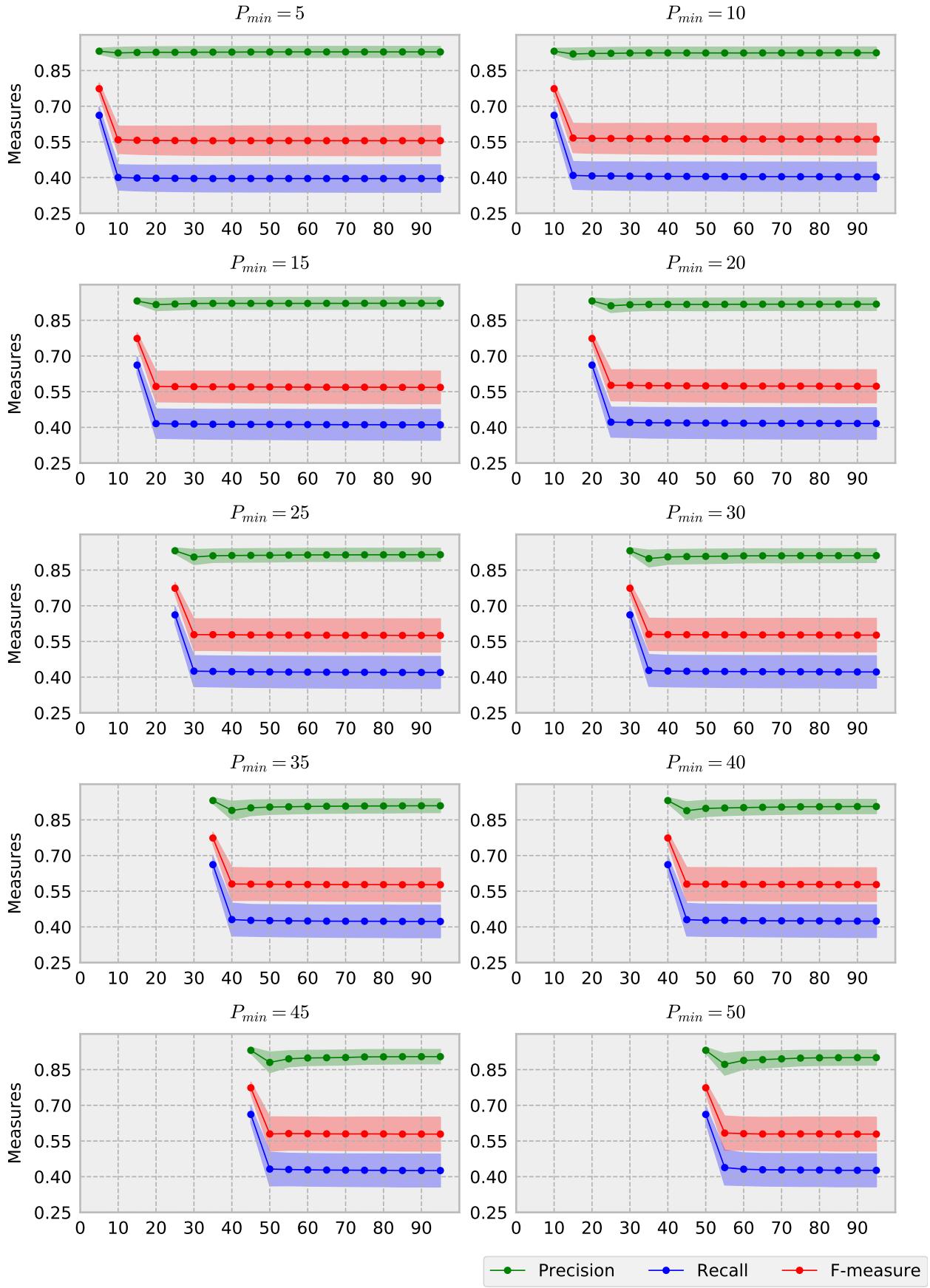


Figure 5.15: Scatter plot with the quality measures for grid search parameters in SFA dataset.

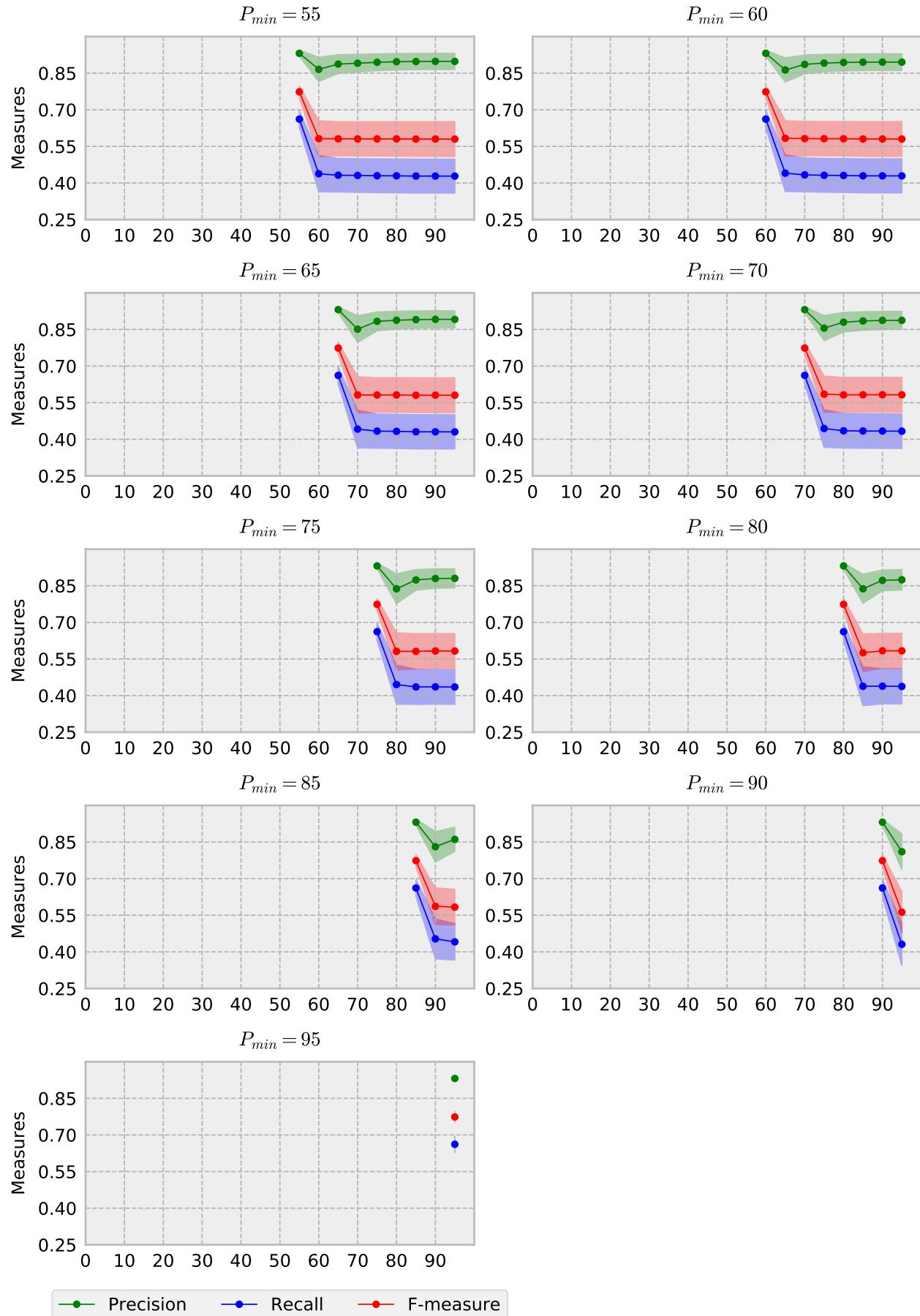


Figure 5.15: Scatter plot with the quality measures for grid search parameters in SFA dataset (cont.).

Chapter 6

Conclusions

We started this thesis by describing the problem of skin detection, explaining our motivation and determining our main objectives. Further, we reviewed the literature with a large number of works of skin detection based on color information, comparing their differences in terms of techniques and classifiers, mainly from the point of view of performance, color models, skin color modeling and datasets. Next, we stated the theoretical concepts that apply to this research where we briefly showed some techniques from image processing and computer vision fields used during the project, such as color space transformation, human skin segmentation and understanding, etc. Then, we reviewed the method proposed by [Brancati et al. \(2017\)](#) and we added new variations of it. Also, we showed an implementation of a grid search strategy to figure out the best combination of parameters to the method. Finally, we presented some experimental evaluations of the proposed extensions along with the original method in four widely known datasets: SFA, Pratheepan, HGR, and Compaq.

This chapter comes this thesis to an end by addressing our conclusions regarding our research, objectives, and contributions. In section 6.1 we do a brief summary of the whole time line of this research project and sum up the final considerations. Lastly, in section 6.2 we compile the set of future work that can potentially bring our research even closer to better solutions.

6.1 Final considerations

The credits in the required subjects for the master's program in Computer Science at IME-USP were fulfilled from March 2015 until June 2016, according to the table 6.1. Thereafter, we started the bibliographic research for the development of this project. During this period up to the examining committee, preliminary experiments were carried out which served as a basis for subsequent steps. It is worth mentioning that the most important recommendation was done by a Committee's member, Prof. Dr. Roberto Marcondes, who has indicated for us the fundamental related paper of this work.

| Code | Name | Conclusion |
|---------|---|------------|
| MAC5832 | Machine Learning: Models, Algorithms and Applications | Jun/2015 |
| MAC5744 | Introduction to Computer Graphics | Jun/2015 |
| MAC5768 | Computer Vision and Image Processing - Part I | Jun/2015 |
| MAC5711 | Analysis of Algorithms | Nov/2015 |
| MAC6914 | Learning Methods in Computer Vision | Nov/2015 |
| MAC4722 | Languages, Automata and Computability | Jun/2016 |
| MAC5714 | Object-Oriented Programming | Jun/2016 |

Table 6.1: Subjects taken in the course of the master's program in Computer Science at IME-USP.

This paper, proposed by [Brancati et al. \(2017\)](#), is a novel rule-based skin detection method that works in the YCbCr color space based on correlation rules that evaluate the combinations of chrominance Cb, Cr values to identify human skin pixels depending on the shape and size of dynamically generated skin color clusters (trapezoids).

Despite dozens of works in this field, using different techniques other than rule-based, human skin segmentation is still an unsolved problem, mainly for the case of real time applications. In Brancati *et al.* (2017), a surprisingly simple and clever method has been presented and it established a new tier.

We reproduced the original experiments and also checked if the same patterns were presented in RGB, HSV, and Lab color spaces, or other applications as finding tree leaves, but the results were not consistent as the original approach for human skin using YCbCr space.

In this research project, we introduced two extensions based on a hypothesis that the original rule could be reversed and also taking in consideration that a human skin pixel does not appear isolated. A third extension combines the original rule with the reversed one in a more strengthen method in terms of precision. All these extensions are simple and do not hurt the efficiency of the original method.

We tested the extensions in four standard public datasets and the experiments showed that our methods improve the accuracy of skin detection, even when there exists a huge variation in ethnicity and illumination. Moreover, our approach proved to be very competitive, outperforming alternative state-of-the-art work. In addition, we implemented the grid search for the parameters tuning and the supplementary neighborhood operations as well as new tools to process the datasets, binarize images, and a visualization web application for the problem of skin detection¹.

Our results confirm that skin color is an extremely powerful cue for detecting human skin in unconstrained imagery. Other local properties can be experimented to be used in a future work, along with the methods presented here, such as texture, shape, geometry, and other neighborhood operations.

Thus, we can say that the main objective of this research – create or improve new methods for skin detection, according to the rule-based approach – has been successfully completed. More specifically, the main objective to achieve improvements in the method proposed by Brancati *et al.* (2017) in order to reduce the false positive rate. Furthermore, we proposed a deep analysis on the parameters choice for the trapezoids definition which started a new discussion as well as the possibility to apply neighborhood operations.

Additionally, we have accomplished the secondary objectives by publishing a paper in VISAPP conference as well as completing the master's degree in about three years, that is extremely close to the time line set in the beginning of this journey.

6.2 Future work

In the future, extended works could explore further the connectivity of the skin pixels and, because there is so far no explanation why the original method works so well, it would be valuable to statistically analyze the shape of the trapezoids on the YCbCr space and try to correlate with the classification accuracy.

Our intuition, based on the experimental results, says that trapezoids features such as size, area, symmetry and others, could be used to establish a relation with the classification accuracy. Moreover, if this relationship exists, the shape of the trapezoids could be previously processed, for instance by filtering image illumination, to obtain better classification results.

The supplementary neighborhood operations given in section 4.4 will add some additional computational cost once we will scan the image one more time. Primarily, the idea of those variations is to only explore better the connectivity of the 8-neighbors window and check, on the basis of a symmetric mask window, if the *diagonal effect* is gone as well as the measures could be improved. This implementation can be enhanced as well as other techniques applied, such as applying weights when counting neighboring pixels.

We have also implemented a grid search algorithm to understand the parameters selection in section 5.5. However, additional experiments can be made on this topic. A good suggestion would

¹ Available at <https://bitbucket.org/rodrigoadfaria/skin-detector-ws>.

involve a new method to learn the best parameters of the trapezoids by means of machine learning techniques.

We have checked if the same patterns would appear in RGB, HSV, and Lab color spaces, the results were not consistent as the original approach for human skin using YCbCr space. However, a surprisingly comparison between different color spaces in Chaves-González *et al.* (2010) suggests that YCgCr is a very good candidate for this problem. In fact, YCbCr and YCgCr color spaces are very similar. Therefore, if one finds out the same patterns (trapezoids shapes) appear in this space, he/she could obtain a better result, because green color is quite better than blue color to detect skin, so it is a very worthwhile change.

Appendix A

Trapezoids Parameters Tuning Results

In this appendix we present the results of the grid search algorithm applied on each of the four datasets described in section 5.1. We only applied the combined rules method, once the trapezoids parameters definition do not change among the different methods, as described in chapter 4. Every table is sorted by *F-measure*, *Precision* and *Recall*, respectively. The results are presented in Tables A.1, A.2 A.3, and A.4 for Compaq, Pratheepan, HGR, and SFA, respectively.

Table A.1: Trapezoids parameters tuning results for Compaq dataset and combined rules.

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 5 | 25 | 0.4819 | 0.6459 | 0.8762 | 0.5520 |
| 5 | 35 | 0.4866 | 0.6374 | 0.8808 | 0.5519 |
| 5 | 40 | 0.4877 | 0.6356 | 0.8818 | 0.5519 |
| 5 | 30 | 0.4844 | 0.6408 | 0.8789 | 0.5517 |
| 5 | 45 | 0.4884 | 0.6335 | 0.8827 | 0.5516 |
| 5 | 20 | 0.4784 | 0.6508 | 0.8729 | 0.5514 |
| 5 | 55 | 0.4901 | 0.6303 | 0.8843 | 0.5514 |
| 5 | 50 | 0.4887 | 0.6318 | 0.8832 | 0.5511 |
| 5 | 60 | 0.4904 | 0.6288 | 0.8848 | 0.5511 |
| 5 | 65 | 0.4906 | 0.6279 | 0.8852 | 0.5509 |
| 5 | 70 | 0.4908 | 0.6272 | 0.8854 | 0.5507 |
| 5 | 75 | 0.4907 | 0.6266 | 0.8855 | 0.5504 |
| 5 | 80 | 0.4907 | 0.6261 | 0.8856 | 0.5502 |
| 5 | 85 | 0.4907 | 0.6256 | 0.8857 | 0.5500 |
| 5 | 90 | 0.4908 | 0.6253 | 0.8858 | 0.5500 |
| 5 | 95 | 0.4908 | 0.6251 | 0.8858 | 0.5499 |
| 10 | 55 | 0.4838 | 0.6313 | 0.8808 | 0.5478 |
| 10 | 40 | 0.4806 | 0.6364 | 0.8777 | 0.5477 |
| 10 | 35 | 0.4794 | 0.6382 | 0.8768 | 0.5475 |
| 10 | 45 | 0.4817 | 0.6341 | 0.8788 | 0.5475 |
| 10 | 60 | 0.4842 | 0.6297 | 0.8813 | 0.5474 |
| 10 | 65 | 0.4844 | 0.6287 | 0.8816 | 0.5472 |
| 10 | 50 | 0.4822 | 0.6324 | 0.8794 | 0.5472 |
| 10 | 70 | 0.4846 | 0.6281 | 0.8818 | 0.5471 |
| 10 | 30 | 0.4767 | 0.6414 | 0.8746 | 0.5469 |
| 10 | 25 | 0.4738 | 0.6465 | 0.8715 | 0.5468 |
| 10 | 75 | 0.4845 | 0.6274 | 0.8819 | 0.5468 |
| 10 | 80 | 0.4845 | 0.6269 | 0.8820 | 0.5466 |
| 10 | 85 | 0.4845 | 0.6263 | 0.8821 | 0.5464 |
| 10 | 90 | 0.4846 | 0.6260 | 0.8822 | 0.5463 |
| 10 | 95 | 0.4846 | 0.6258 | 0.8823 | 0.5462 |
| 5 | 15 | 0.4688 | 0.6520 | 0.8683 | 0.5455 |
| 10 | 20 | 0.4689 | 0.6515 | 0.8675 | 0.5453 |
| 15 | 55 | 0.4784 | 0.6331 | 0.8773 | 0.5450 |
| 15 | 60 | 0.4789 | 0.6315 | 0.8779 | 0.5447 |

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Table A.1 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 15 | 65 | 0.4793 | 0.6305 | 0.8784 | 0.5446 |
| 15 | 70 | 0.4795 | 0.6300 | 0.8786 | 0.5446 |
| 15 | 45 | 0.4761 | 0.6358 | 0.8752 | 0.5445 |
| 15 | 40 | 0.4747 | 0.6382 | 0.8740 | 0.5444 |
| 15 | 75 | 0.4794 | 0.6293 | 0.8787 | 0.5442 |
| 15 | 50 | 0.4766 | 0.6339 | 0.8759 | 0.5441 |
| 15 | 80 | 0.4796 | 0.6287 | 0.8789 | 0.5441 |
| 15 | 35 | 0.4730 | 0.6401 | 0.8728 | 0.5440 |
| 15 | 85 | 0.4795 | 0.6281 | 0.8790 | 0.5439 |
| 15 | 90 | 0.4797 | 0.6279 | 0.8792 | 0.5438 |
| 15 | 95 | 0.4796 | 0.6277 | 0.8792 | 0.5437 |
| 20 | 55 | 0.4742 | 0.6352 | 0.8747 | 0.5430 |
| 20 | 60 | 0.4748 | 0.6336 | 0.8755 | 0.5429 |
| 20 | 65 | 0.4753 | 0.6326 | 0.8759 | 0.5428 |
| 15 | 30 | 0.4692 | 0.6434 | 0.8701 | 0.5427 |
| 20 | 70 | 0.4755 | 0.6320 | 0.8761 | 0.5427 |
| 20 | 75 | 0.4755 | 0.6312 | 0.8764 | 0.5424 |
| 20 | 80 | 0.4756 | 0.6306 | 0.8766 | 0.5423 |
| 20 | 45 | 0.4714 | 0.6375 | 0.8725 | 0.5420 |
| 20 | 90 | 0.4758 | 0.6297 | 0.8769 | 0.5420 |
| 20 | 85 | 0.4757 | 0.6299 | 0.8768 | 0.5420 |
| 20 | 50 | 0.4722 | 0.6360 | 0.8732 | 0.5420 |
| 20 | 95 | 0.4757 | 0.6296 | 0.8769 | 0.5419 |
| 20 | 40 | 0.4696 | 0.6401 | 0.8710 | 0.5418 |
| 20 | 35 | 0.4674 | 0.6428 | 0.8690 | 0.5412 |
| 25 | 55 | 0.4702 | 0.6374 | 0.8719 | 0.5412 |
| 25 | 70 | 0.4720 | 0.6337 | 0.8736 | 0.5410 |
| 25 | 65 | 0.4716 | 0.6343 | 0.8734 | 0.5410 |
| 25 | 60 | 0.4709 | 0.6355 | 0.8728 | 0.5410 |
| 25 | 75 | 0.4722 | 0.6328 | 0.8740 | 0.5408 |
| 15 | 25 | 0.4639 | 0.6482 | 0.8647 | 0.5408 |
| 25 | 80 | 0.4724 | 0.6319 | 0.8742 | 0.5407 |
| 25 | 85 | 0.4726 | 0.6312 | 0.8744 | 0.5405 |
| 25 | 90 | 0.4727 | 0.6310 | 0.8746 | 0.5405 |
| 25 | 95 | 0.4726 | 0.6309 | 0.8746 | 0.5404 |
| 25 | 45 | 0.4672 | 0.6403 | 0.8695 | 0.5402 |
| 25 | 50 | 0.4681 | 0.6385 | 0.8703 | 0.5402 |
| 30 | 70 | 0.4687 | 0.6353 | 0.8714 | 0.5395 |
| 30 | 75 | 0.4690 | 0.6343 | 0.8719 | 0.5393 |
| 30 | 80 | 0.4694 | 0.6333 | 0.8722 | 0.5391 |
| 30 | 90 | 0.4698 | 0.6325 | 0.8726 | 0.5391 |
| 30 | 65 | 0.4679 | 0.6359 | 0.8711 | 0.5391 |
| 30 | 95 | 0.4698 | 0.6323 | 0.8726 | 0.5391 |
| 30 | 85 | 0.4695 | 0.6327 | 0.8724 | 0.5390 |
| 30 | 60 | 0.4670 | 0.6373 | 0.8704 | 0.5390 |
| 30 | 55 | 0.4659 | 0.6390 | 0.8693 | 0.5389 |
| 25 | 40 | 0.4635 | 0.6431 | 0.8662 | 0.5387 |
| 35 | 70 | 0.4663 | 0.6365 | 0.8697 | 0.5383 |
| 35 | 75 | 0.4667 | 0.6355 | 0.8702 | 0.5382 |
| 35 | 90 | 0.4675 | 0.6337 | 0.8709 | 0.5380 |
| 35 | 95 | 0.4675 | 0.6336 | 0.8709 | 0.5380 |
| 35 | 85 | 0.4672 | 0.6339 | 0.8707 | 0.5379 |
| 35 | 80 | 0.4669 | 0.6344 | 0.8705 | 0.5379 |
| 5 | 10 | 0.4547 | 0.6577 | 0.8579 | 0.5377 |
| 20 | 30 | 0.4605 | 0.6455 | 0.8644 | 0.5375 |
| 25 | 35 | 0.4598 | 0.6463 | 0.8630 | 0.5373 |
| 35 | 65 | 0.4646 | 0.6370 | 0.8689 | 0.5373 |
| 30 | 50 | 0.4627 | 0.6404 | 0.8668 | 0.5372 |
| 35 | 60 | 0.4635 | 0.6385 | 0.8680 | 0.5371 |

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Table A.1 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 40 | 70 | 0.4637 | 0.6376 | 0.8681 | 0.5369 |
| 40 | 75 | 0.4641 | 0.6366 | 0.8686 | 0.5368 |
| 35 | 55 | 0.4620 | 0.6405 | 0.8665 | 0.5368 |
| 40 | 90 | 0.4650 | 0.6347 | 0.8695 | 0.5367 |
| 40 | 95 | 0.4650 | 0.6346 | 0.8695 | 0.5367 |
| 40 | 85 | 0.4647 | 0.6349 | 0.8693 | 0.5367 |
| 40 | 80 | 0.4644 | 0.6355 | 0.8691 | 0.5366 |
| 30 | 45 | 0.4605 | 0.6426 | 0.8653 | 0.5365 |
| 40 | 65 | 0.4616 | 0.6385 | 0.8671 | 0.5358 |
| 40 | 60 | 0.4600 | 0.6402 | 0.8659 | 0.5354 |
| 45 | 75 | 0.4609 | 0.6378 | 0.8663 | 0.5351 |
| 45 | 90 | 0.4620 | 0.6356 | 0.8675 | 0.5351 |
| 45 | 80 | 0.4615 | 0.6365 | 0.8670 | 0.5350 |
| 45 | 95 | 0.4620 | 0.6354 | 0.8676 | 0.5350 |
| 45 | 85 | 0.4617 | 0.6359 | 0.8673 | 0.5350 |
| 45 | 70 | 0.4602 | 0.6388 | 0.8656 | 0.5350 |
| 10 | 15 | 0.4534 | 0.6521 | 0.8575 | 0.5349 |
| 40 | 55 | 0.4576 | 0.6426 | 0.8639 | 0.5346 |
| 50 | 75 | 0.4585 | 0.6400 | 0.8646 | 0.5343 |
| 50 | 85 | 0.4596 | 0.6379 | 0.8657 | 0.5342 |
| 50 | 80 | 0.4592 | 0.6386 | 0.8653 | 0.5342 |
| 50 | 90 | 0.4598 | 0.6373 | 0.8660 | 0.5342 |
| 50 | 95 | 0.4599 | 0.6371 | 0.8661 | 0.5342 |
| 50 | 70 | 0.4574 | 0.6417 | 0.8634 | 0.5341 |
| 45 | 65 | 0.4576 | 0.6401 | 0.8641 | 0.5337 |
| 15 | 20 | 0.4509 | 0.6509 | 0.8541 | 0.5327 |
| 50 | 65 | 0.4543 | 0.6434 | 0.8614 | 0.5326 |
| 55 | 90 | 0.4562 | 0.6390 | 0.8635 | 0.5324 |
| 55 | 85 | 0.4559 | 0.6396 | 0.8631 | 0.5323 |
| 55 | 95 | 0.4563 | 0.6387 | 0.8636 | 0.5323 |
| 55 | 80 | 0.4552 | 0.6403 | 0.8627 | 0.5321 |
| 45 | 60 | 0.4544 | 0.6414 | 0.8622 | 0.5320 |
| 30 | 40 | 0.4533 | 0.6436 | 0.8604 | 0.5319 |
| 5 | 5 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 10 | 10 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 15 | 15 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 20 | 20 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 25 | 25 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 30 | 30 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 35 | 35 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 40 | 40 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 45 | 45 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 50 | 50 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 55 | 55 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 60 | 60 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 65 | 65 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 70 | 70 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 75 | 75 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 80 | 80 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 85 | 85 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 90 | 90 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 95 | 95 | 0.4172 | 0.7333 | 0.8096 | 0.5318 |
| 55 | 75 | 0.4532 | 0.6420 | 0.8608 | 0.5313 |
| 60 | 90 | 0.4536 | 0.6409 | 0.8611 | 0.5312 |
| 60 | 95 | 0.4537 | 0.6406 | 0.8612 | 0.5312 |
| 60 | 85 | 0.4530 | 0.6415 | 0.8606 | 0.5310 |
| 55 | 70 | 0.4513 | 0.6440 | 0.8592 | 0.5307 |
| 60 | 80 | 0.4519 | 0.6422 | 0.8597 | 0.5305 |
| 35 | 50 | 0.4536 | 0.6385 | 0.8616 | 0.5304 |

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Table A.1 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 50 | 60 | 0.4496 | 0.6453 | 0.8582 | 0.5299 |
| 65 | 95 | 0.4509 | 0.6424 | 0.8593 | 0.5299 |
| 65 | 90 | 0.4506 | 0.6428 | 0.8590 | 0.5298 |
| 60 | 75 | 0.4494 | 0.6445 | 0.8572 | 0.5295 |
| 65 | 85 | 0.4494 | 0.6437 | 0.8582 | 0.5293 |
| 45 | 55 | 0.4494 | 0.6436 | 0.8582 | 0.5293 |
| 35 | 45 | 0.4492 | 0.6414 | 0.8575 | 0.5284 |
| 65 | 80 | 0.4463 | 0.6446 | 0.8550 | 0.5274 |
| 60 | 70 | 0.4444 | 0.6469 | 0.8528 | 0.5269 |
| 70 | 95 | 0.4457 | 0.6415 | 0.8567 | 0.5260 |
| 70 | 90 | 0.4451 | 0.6423 | 0.8560 | 0.5258 |
| 70 | 85 | 0.4437 | 0.6437 | 0.8546 | 0.5253 |
| 55 | 65 | 0.4436 | 0.6435 | 0.8533 | 0.5252 |
| 40 | 50 | 0.4450 | 0.6403 | 0.8554 | 0.5251 |
| 30 | 35 | 0.4413 | 0.6477 | 0.8494 | 0.5249 |
| 25 | 30 | 0.4419 | 0.6462 | 0.8490 | 0.5248 |
| 20 | 25 | 0.4418 | 0.6453 | 0.8515 | 0.5245 |
| 65 | 75 | 0.4412 | 0.6465 | 0.8499 | 0.5245 |
| 75 | 95 | 0.4409 | 0.6427 | 0.8528 | 0.5230 |
| 75 | 90 | 0.4398 | 0.6440 | 0.8519 | 0.5226 |
| 50 | 55 | 0.4357 | 0.6461 | 0.8459 | 0.5205 |
| 80 | 95 | 0.4352 | 0.6467 | 0.8451 | 0.5203 |
| 75 | 85 | 0.4348 | 0.6449 | 0.8486 | 0.5194 |
| 80 | 90 | 0.4327 | 0.6483 | 0.8433 | 0.5190 |
| 70 | 80 | 0.4352 | 0.6418 | 0.8486 | 0.5187 |
| 40 | 45 | 0.4329 | 0.6437 | 0.8428 | 0.5176 |
| 35 | 40 | 0.4313 | 0.6381 | 0.8476 | 0.5147 |
| 55 | 60 | 0.4250 | 0.6395 | 0.8417 | 0.5107 |
| 65 | 70 | 0.4219 | 0.6453 | 0.8335 | 0.5102 |
| 45 | 50 | 0.4247 | 0.6381 | 0.8413 | 0.5100 |
| 60 | 65 | 0.4203 | 0.6402 | 0.8354 | 0.5075 |
| 85 | 95 | 0.4168 | 0.6397 | 0.8335 | 0.5048 |
| 70 | 75 | 0.4129 | 0.6405 | 0.8269 | 0.5021 |
| 75 | 80 | 0.4091 | 0.6383 | 0.8289 | 0.4986 |
| 80 | 85 | 0.4056 | 0.6423 | 0.8215 | 0.4972 |
| 85 | 90 | 0.3967 | 0.6332 | 0.8199 | 0.4878 |
| 90 | 95 | 0.3869 | 0.6323 | 0.8080 | 0.4801 |

Table A.2: Trapezoids parameters tuning results for Pratheepan dataset and combined rules.

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 10 | 55 | 0.6560 | 0.6955 | 0.9055 | 0.6752 |
| 10 | 80 | 0.6558 | 0.6950 | 0.9056 | 0.6748 |
| 10 | 85 | 0.6557 | 0.6949 | 0.9056 | 0.6748 |
| 10 | 95 | 0.6557 | 0.6950 | 0.9057 | 0.6747 |
| 10 | 90 | 0.6556 | 0.6950 | 0.9056 | 0.6747 |
| 10 | 50 | 0.6551 | 0.6953 | 0.9052 | 0.6746 |
| 10 | 75 | 0.6561 | 0.6935 | 0.9057 | 0.6743 |
| 5 | 15 | 0.6521 | 0.6978 | 0.9045 | 0.6741 |
| 10 | 25 | 0.6509 | 0.6991 | 0.9057 | 0.6741 |
| 10 | 60 | 0.6563 | 0.6928 | 0.9057 | 0.6740 |
| 10 | 30 | 0.6508 | 0.6983 | 0.9045 | 0.6737 |
| 10 | 65 | 0.6563 | 0.6920 | 0.9057 | 0.6737 |
| 10 | 70 | 0.6562 | 0.6920 | 0.9057 | 0.6736 |
| 10 | 45 | 0.6530 | 0.6955 | 0.9048 | 0.6736 |
| 10 | 35 | 0.6510 | 0.6972 | 0.9044 | 0.6733 |

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Table A.2 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 10 | 15 | 0.6376 | 0.7133 | 0.8916 | 0.6733 |
| 10 | 40 | 0.6525 | 0.6945 | 0.9048 | 0.6728 |
| 5 | 55 | 0.6595 | 0.6852 | 0.9085 | 0.6721 |
| 10 | 20 | 0.6425 | 0.7039 | 0.8985 | 0.6718 |
| 5 | 50 | 0.6591 | 0.6850 | 0.9084 | 0.6718 |
| 5 | 60 | 0.6599 | 0.6827 | 0.9087 | 0.6711 |
| 5 | 45 | 0.6577 | 0.6848 | 0.9083 | 0.6710 |
| 15 | 35 | 0.6487 | 0.6939 | 0.9040 | 0.6706 |
| 5 | 65 | 0.6600 | 0.6813 | 0.9087 | 0.6705 |
| 5 | 40 | 0.6570 | 0.6842 | 0.9084 | 0.6704 |
| 5 | 70 | 0.6599 | 0.6811 | 0.9087 | 0.6703 |
| 5 | 30 | 0.6550 | 0.6861 | 0.9080 | 0.6702 |
| 5 | 35 | 0.6553 | 0.6858 | 0.9080 | 0.6702 |
| 5 | 20 | 0.6522 | 0.6891 | 0.9068 | 0.6701 |
| 5 | 95 | 0.6596 | 0.6809 | 0.9088 | 0.6701 |
| 5 | 90 | 0.6595 | 0.6810 | 0.9088 | 0.6701 |
| 5 | 80 | 0.6595 | 0.6806 | 0.9088 | 0.6699 |
| 5 | 25 | 0.6538 | 0.6868 | 0.9076 | 0.6699 |
| 5 | 85 | 0.6595 | 0.6805 | 0.9088 | 0.6698 |
| 15 | 50 | 0.6503 | 0.6904 | 0.9028 | 0.6698 |
| 15 | 30 | 0.6475 | 0.6935 | 0.9040 | 0.6697 |
| 20 | 45 | 0.6397 | 0.7024 | 0.8915 | 0.6696 |
| 15 | 45 | 0.6478 | 0.6924 | 0.9021 | 0.6694 |
| 20 | 30 | 0.6347 | 0.7077 | 0.8934 | 0.6692 |
| 15 | 55 | 0.6494 | 0.6900 | 0.9027 | 0.6691 |
| 15 | 65 | 0.6503 | 0.6879 | 0.9030 | 0.6686 |
| 20 | 40 | 0.6389 | 0.7012 | 0.8913 | 0.6686 |
| 15 | 80 | 0.6489 | 0.6893 | 0.9028 | 0.6685 |
| 5 | 75 | 0.6595 | 0.6776 | 0.9088 | 0.6685 |
| 15 | 40 | 0.6474 | 0.6909 | 0.9021 | 0.6684 |
| 15 | 85 | 0.6488 | 0.6891 | 0.9028 | 0.6683 |
| 20 | 50 | 0.6418 | 0.6971 | 0.8925 | 0.6683 |
| 15 | 75 | 0.6493 | 0.6884 | 0.9029 | 0.6683 |
| 15 | 95 | 0.6487 | 0.6891 | 0.9028 | 0.6683 |
| 15 | 90 | 0.6487 | 0.6891 | 0.9028 | 0.6683 |
| 15 | 60 | 0.6503 | 0.6873 | 0.9030 | 0.6683 |
| 20 | 35 | 0.6373 | 0.7022 | 0.8938 | 0.6682 |
| 20 | 25 | 0.6271 | 0.7144 | 0.8855 | 0.6679 |
| 15 | 70 | 0.6494 | 0.6872 | 0.9029 | 0.6678 |
| 20 | 55 | 0.6409 | 0.6967 | 0.8923 | 0.6676 |
| 20 | 65 | 0.6420 | 0.6944 | 0.8927 | 0.6672 |
| 15 | 25 | 0.6420 | 0.6943 | 0.8992 | 0.6672 |
| 20 | 60 | 0.6419 | 0.6937 | 0.8926 | 0.6668 |
| 20 | 75 | 0.6411 | 0.6938 | 0.8927 | 0.6664 |
| 20 | 70 | 0.6412 | 0.6933 | 0.8927 | 0.6662 |
| 35 | 40 | 0.6196 | 0.7195 | 0.8793 | 0.6658 |
| 35 | 45 | 0.6208 | 0.7155 | 0.8746 | 0.6648 |
| 35 | 50 | 0.6246 | 0.7077 | 0.8776 | 0.6635 |
| 35 | 55 | 0.6242 | 0.7078 | 0.8774 | 0.6634 |
| 20 | 80 | 0.6349 | 0.6941 | 0.8874 | 0.6632 |
| 30 | 50 | 0.6295 | 0.7004 | 0.8832 | 0.6631 |
| 20 | 90 | 0.6348 | 0.6939 | 0.8875 | 0.6630 |
| 20 | 95 | 0.6348 | 0.6938 | 0.8875 | 0.6630 |
| 20 | 85 | 0.6348 | 0.6938 | 0.8875 | 0.6630 |
| 30 | 55 | 0.6293 | 0.7003 | 0.8828 | 0.6629 |
| 30 | 45 | 0.6256 | 0.7045 | 0.8815 | 0.6627 |
| 5 | 5 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 10 | 10 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 15 | 15 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |

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Table A.2 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 20 | 20 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 25 | 25 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 30 | 30 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 35 | 35 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 40 | 40 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 45 | 45 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 50 | 50 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 55 | 55 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 60 | 60 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 65 | 65 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 70 | 70 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 75 | 75 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 80 | 80 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 85 | 85 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 90 | 90 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 95 | 95 | 0.5587 | 0.8129 | 0.8327 | 0.6623 |
| 25 | 45 | 0.6254 | 0.7029 | 0.8815 | 0.6619 |
| 25 | 55 | 0.6290 | 0.6979 | 0.8833 | 0.6617 |
| 25 | 50 | 0.6286 | 0.6977 | 0.8831 | 0.6614 |
| 35 | 65 | 0.6247 | 0.7026 | 0.8780 | 0.6614 |
| 30 | 65 | 0.6295 | 0.6965 | 0.8832 | 0.6613 |
| 30 | 60 | 0.6295 | 0.6966 | 0.8836 | 0.6613 |
| 35 | 60 | 0.6244 | 0.7029 | 0.8780 | 0.6613 |
| 40 | 45 | 0.6094 | 0.7224 | 0.8662 | 0.6611 |
| 25 | 65 | 0.6298 | 0.6947 | 0.8840 | 0.6607 |
| 25 | 60 | 0.6296 | 0.6944 | 0.8840 | 0.6604 |
| 35 | 85 | 0.6252 | 0.6994 | 0.8808 | 0.6602 |
| 35 | 95 | 0.6251 | 0.6995 | 0.8807 | 0.6602 |
| 35 | 90 | 0.6251 | 0.6995 | 0.8808 | 0.6602 |
| 25 | 75 | 0.6291 | 0.6940 | 0.8842 | 0.6600 |
| 25 | 70 | 0.6291 | 0.6938 | 0.8841 | 0.6599 |
| 30 | 40 | 0.6219 | 0.7027 | 0.8804 | 0.6598 |
| 25 | 80 | 0.6284 | 0.6942 | 0.8837 | 0.6597 |
| 25 | 90 | 0.6284 | 0.6942 | 0.8836 | 0.6597 |
| 25 | 95 | 0.6284 | 0.6942 | 0.8836 | 0.6597 |
| 35 | 70 | 0.6244 | 0.6991 | 0.8802 | 0.6596 |
| 25 | 85 | 0.6284 | 0.6941 | 0.8837 | 0.6596 |
| 35 | 75 | 0.6243 | 0.6987 | 0.8802 | 0.6594 |
| 30 | 70 | 0.6277 | 0.6939 | 0.8832 | 0.6592 |
| 30 | 75 | 0.6277 | 0.6939 | 0.8832 | 0.6592 |
| 25 | 40 | 0.6222 | 0.7006 | 0.8803 | 0.6591 |
| 65 | 90 | 0.6073 | 0.7206 | 0.8680 | 0.6591 |
| 65 | 95 | 0.6071 | 0.7206 | 0.8680 | 0.6590 |
| 35 | 80 | 0.6235 | 0.6987 | 0.8802 | 0.6590 |
| 30 | 80 | 0.6272 | 0.6938 | 0.8832 | 0.6589 |
| 30 | 95 | 0.6271 | 0.6937 | 0.8831 | 0.6587 |
| 30 | 85 | 0.6272 | 0.6936 | 0.8832 | 0.6587 |
| 30 | 90 | 0.6271 | 0.6937 | 0.8832 | 0.6587 |
| 65 | 85 | 0.6055 | 0.7215 | 0.8676 | 0.6584 |
| 45 | 65 | 0.6151 | 0.7061 | 0.8718 | 0.6575 |
| 5 | 10 | 0.6257 | 0.6907 | 0.8921 | 0.6566 |
| 40 | 50 | 0.6117 | 0.7087 | 0.8709 | 0.6566 |
| 40 | 65 | 0.6167 | 0.7011 | 0.8739 | 0.6562 |
| 40 | 55 | 0.6126 | 0.7063 | 0.8714 | 0.6561 |
| 60 | 90 | 0.6097 | 0.7095 | 0.8699 | 0.6558 |
| 60 | 70 | 0.6074 | 0.7125 | 0.8707 | 0.6558 |
| 25 | 35 | 0.6163 | 0.7004 | 0.8792 | 0.6557 |
| 50 | 65 | 0.6117 | 0.7064 | 0.8712 | 0.6556 |
| 60 | 95 | 0.6093 | 0.7094 | 0.8697 | 0.6556 |

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Table A.2 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 45 | 95 | 0.6153 | 0.7012 | 0.8750 | 0.6554 |
| 65 | 80 | 0.6017 | 0.7197 | 0.8661 | 0.6554 |
| 45 | 90 | 0.6153 | 0.7012 | 0.8750 | 0.6554 |
| 40 | 60 | 0.6154 | 0.7009 | 0.8742 | 0.6554 |
| 60 | 85 | 0.6079 | 0.7104 | 0.8697 | 0.6552 |
| 45 | 85 | 0.6151 | 0.7007 | 0.8750 | 0.6551 |
| 40 | 95 | 0.6163 | 0.6991 | 0.8762 | 0.6551 |
| 40 | 90 | 0.6163 | 0.6991 | 0.8762 | 0.6551 |
| 40 | 85 | 0.6163 | 0.6989 | 0.8763 | 0.6550 |
| 70 | 95 | 0.6004 | 0.7204 | 0.8650 | 0.6549 |
| 45 | 70 | 0.6149 | 0.7005 | 0.8749 | 0.6549 |
| 70 | 90 | 0.6001 | 0.7202 | 0.8647 | 0.6547 |
| 40 | 70 | 0.6163 | 0.6981 | 0.8762 | 0.6546 |
| 50 | 95 | 0.6124 | 0.7031 | 0.8740 | 0.6546 |
| 50 | 90 | 0.6124 | 0.7030 | 0.8740 | 0.6546 |
| 40 | 75 | 0.6161 | 0.6979 | 0.8760 | 0.6545 |
| 70 | 85 | 0.5984 | 0.7218 | 0.8644 | 0.6544 |
| 45 | 75 | 0.6145 | 0.6996 | 0.8748 | 0.6543 |
| 50 | 85 | 0.6121 | 0.7025 | 0.8740 | 0.6542 |
| 45 | 80 | 0.6138 | 0.6998 | 0.8745 | 0.6540 |
| 55 | 90 | 0.6100 | 0.7049 | 0.8722 | 0.6540 |
| 55 | 95 | 0.6098 | 0.7051 | 0.8719 | 0.6540 |
| 40 | 80 | 0.6148 | 0.6978 | 0.8758 | 0.6537 |
| 60 | 80 | 0.6053 | 0.7099 | 0.8688 | 0.6534 |
| 50 | 70 | 0.6111 | 0.7020 | 0.8736 | 0.6534 |
| 50 | 75 | 0.6113 | 0.7015 | 0.8738 | 0.6533 |
| 55 | 85 | 0.6083 | 0.7053 | 0.8721 | 0.6532 |
| 50 | 80 | 0.6108 | 0.7016 | 0.8735 | 0.6530 |
| 15 | 20 | 0.6174 | 0.6924 | 0.8838 | 0.6528 |
| 60 | 75 | 0.6059 | 0.7072 | 0.8686 | 0.6526 |
| 55 | 75 | 0.6073 | 0.7027 | 0.8723 | 0.6515 |
| 55 | 80 | 0.6060 | 0.7038 | 0.8716 | 0.6512 |
| 55 | 70 | 0.6055 | 0.7041 | 0.8713 | 0.6511 |
| 65 | 75 | 0.5980 | 0.7143 | 0.8654 | 0.6510 |
| 45 | 60 | 0.6065 | 0.6967 | 0.8723 | 0.6485 |
| 45 | 55 | 0.6016 | 0.7009 | 0.8689 | 0.6475 |
| 30 | 35 | 0.6015 | 0.6991 | 0.8741 | 0.6466 |
| 80 | 85 | 0.5835 | 0.7235 | 0.8555 | 0.6460 |
| 50 | 60 | 0.6020 | 0.6970 | 0.8703 | 0.6460 |
| 50 | 55 | 0.5952 | 0.7048 | 0.8663 | 0.6454 |
| 80 | 95 | 0.5871 | 0.7165 | 0.8638 | 0.6454 |
| 75 | 85 | 0.5851 | 0.7176 | 0.8640 | 0.6446 |
| 70 | 80 | 0.5880 | 0.7131 | 0.8648 | 0.6445 |
| 80 | 90 | 0.5862 | 0.7154 | 0.8632 | 0.6444 |
| 75 | 95 | 0.5859 | 0.7144 | 0.8638 | 0.6438 |
| 75 | 90 | 0.5859 | 0.7130 | 0.8635 | 0.6432 |
| 25 | 30 | 0.5978 | 0.6921 | 0.8787 | 0.6415 |
| 60 | 65 | 0.5838 | 0.6978 | 0.8689 | 0.6357 |
| 70 | 75 | 0.5776 | 0.7018 | 0.8708 | 0.6337 |
| 65 | 70 | 0.5761 | 0.7027 | 0.8670 | 0.6332 |
| 45 | 50 | 0.5821 | 0.6933 | 0.8669 | 0.6328 |
| 55 | 65 | 0.5842 | 0.6869 | 0.8692 | 0.6314 |
| 85 | 95 | 0.5708 | 0.7028 | 0.8732 | 0.6299 |
| 85 | 90 | 0.5645 | 0.6994 | 0.8702 | 0.6248 |
| 55 | 60 | 0.5703 | 0.6837 | 0.8660 | 0.6219 |
| 75 | 80 | 0.5554 | 0.7039 | 0.8527 | 0.6209 |
| 90 | 95 | 0.5536 | 0.7045 | 0.8603 | 0.6200 |

Table A.3: Trapezoids parameters tuning results for HGR dataset and combined rules.

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 5 | 5 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 10 | 10 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 15 | 15 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 20 | 20 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 25 | 25 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 30 | 30 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 35 | 35 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 40 | 40 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 45 | 45 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 50 | 50 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 55 | 55 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 60 | 60 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 65 | 65 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 70 | 70 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 75 | 75 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 80 | 80 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 85 | 85 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 90 | 90 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 95 | 95 | 0.8693 | 0.8641 | 0.9064 | 0.8667 |
| 25 | 40 | 0.8858 | 0.7323 | 0.9277 | 0.8018 |
| 25 | 45 | 0.8867 | 0.7314 | 0.9288 | 0.8016 |
| 25 | 35 | 0.8836 | 0.7334 | 0.9253 | 0.8015 |
| 25 | 50 | 0.8869 | 0.7311 | 0.9291 | 0.8015 |
| 30 | 50 | 0.8862 | 0.7316 | 0.9284 | 0.8015 |
| 20 | 40 | 0.8881 | 0.7301 | 0.9298 | 0.8014 |
| 50 | 75 | 0.8821 | 0.7342 | 0.9246 | 0.8014 |
| 60 | 80 | 0.8782 | 0.7369 | 0.9211 | 0.8014 |
| 65 | 85 | 0.8757 | 0.7387 | 0.9185 | 0.8014 |
| 50 | 80 | 0.8821 | 0.7342 | 0.9246 | 0.8014 |
| 25 | 55 | 0.8870 | 0.7308 | 0.9294 | 0.8014 |
| 25 | 65 | 0.8870 | 0.7308 | 0.9293 | 0.8013 |
| 50 | 90 | 0.8823 | 0.7339 | 0.9248 | 0.8013 |
| 30 | 45 | 0.8842 | 0.7326 | 0.9263 | 0.8013 |
| 50 | 85 | 0.8823 | 0.7339 | 0.9248 | 0.8013 |
| 50 | 70 | 0.8791 | 0.7361 | 0.9208 | 0.8013 |
| 25 | 60 | 0.8870 | 0.7307 | 0.9293 | 0.8013 |
| 60 | 85 | 0.8785 | 0.7365 | 0.9213 | 0.8013 |
| 20 | 45 | 0.8881 | 0.7299 | 0.9298 | 0.8013 |
| 65 | 90 | 0.8759 | 0.7384 | 0.9186 | 0.8013 |
| 60 | 90 | 0.8786 | 0.7364 | 0.9214 | 0.8013 |
| 50 | 95 | 0.8823 | 0.7339 | 0.9248 | 0.8012 |
| 55 | 80 | 0.8802 | 0.7353 | 0.9230 | 0.8012 |
| 35 | 50 | 0.8824 | 0.7337 | 0.9243 | 0.8012 |
| 25 | 70 | 0.8868 | 0.7307 | 0.9292 | 0.8012 |
| 30 | 55 | 0.8862 | 0.7311 | 0.9287 | 0.8012 |
| 65 | 95 | 0.8759 | 0.7382 | 0.9187 | 0.8012 |
| 20 | 35 | 0.8877 | 0.7300 | 0.9296 | 0.8012 |
| 25 | 85 | 0.8869 | 0.7306 | 0.9293 | 0.8012 |
| 25 | 80 | 0.8869 | 0.7306 | 0.9293 | 0.8012 |
| 25 | 95 | 0.8869 | 0.7306 | 0.9293 | 0.8012 |
| 25 | 90 | 0.8869 | 0.7305 | 0.9293 | 0.8012 |
| 25 | 75 | 0.8868 | 0.7305 | 0.9292 | 0.8011 |
| 60 | 95 | 0.8786 | 0.7362 | 0.9215 | 0.8011 |
| 55 | 85 | 0.8804 | 0.7350 | 0.9232 | 0.8011 |
| 40 | 65 | 0.8840 | 0.7324 | 0.9269 | 0.8011 |
| 55 | 90 | 0.8804 | 0.7349 | 0.9232 | 0.8011 |
| 30 | 60 | 0.8861 | 0.7309 | 0.9286 | 0.8011 |
| 40 | 80 | 0.8842 | 0.7322 | 0.9271 | 0.8011 |

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Table A.3 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 20 | 50 | 0.8881 | 0.7296 | 0.9298 | 0.8011 |
| 50 | 65 | 0.8770 | 0.7372 | 0.9185 | 0.8011 |
| 30 | 65 | 0.8861 | 0.7309 | 0.9285 | 0.8010 |
| 40 | 95 | 0.8843 | 0.7321 | 0.9271 | 0.8010 |
| 35 | 65 | 0.8851 | 0.7315 | 0.9279 | 0.8010 |
| 40 | 90 | 0.8843 | 0.7321 | 0.9271 | 0.8010 |
| 35 | 55 | 0.8848 | 0.7317 | 0.9276 | 0.8010 |
| 40 | 85 | 0.8842 | 0.7321 | 0.9271 | 0.8010 |
| 35 | 80 | 0.8853 | 0.7314 | 0.9281 | 0.8010 |
| 55 | 95 | 0.8803 | 0.7348 | 0.9232 | 0.8010 |
| 20 | 55 | 0.8882 | 0.7293 | 0.9303 | 0.8010 |
| 20 | 65 | 0.8882 | 0.7294 | 0.9302 | 0.8010 |
| 40 | 70 | 0.8840 | 0.7322 | 0.9267 | 0.8010 |
| 20 | 70 | 0.8882 | 0.7293 | 0.9302 | 0.8009 |
| 40 | 75 | 0.8841 | 0.7321 | 0.9270 | 0.8009 |
| 35 | 90 | 0.8853 | 0.7312 | 0.9282 | 0.8009 |
| 35 | 95 | 0.8853 | 0.7312 | 0.9282 | 0.8009 |
| 35 | 85 | 0.8853 | 0.7312 | 0.9281 | 0.8009 |
| 20 | 60 | 0.8882 | 0.7293 | 0.9301 | 0.8009 |
| 35 | 75 | 0.8852 | 0.7313 | 0.9280 | 0.8009 |
| 35 | 70 | 0.8851 | 0.7314 | 0.9278 | 0.8009 |
| 55 | 75 | 0.8788 | 0.7357 | 0.9212 | 0.8009 |
| 20 | 80 | 0.8882 | 0.7292 | 0.9302 | 0.8009 |
| 35 | 45 | 0.8767 | 0.7372 | 0.9176 | 0.8009 |
| 35 | 60 | 0.8848 | 0.7315 | 0.9276 | 0.8009 |
| 20 | 75 | 0.8882 | 0.7292 | 0.9302 | 0.8009 |
| 30 | 80 | 0.8860 | 0.7307 | 0.9285 | 0.8009 |
| 30 | 70 | 0.8859 | 0.7308 | 0.9284 | 0.8009 |
| 20 | 95 | 0.8882 | 0.7292 | 0.9303 | 0.8009 |
| 20 | 85 | 0.8882 | 0.7292 | 0.9303 | 0.8009 |
| 20 | 90 | 0.8882 | 0.7292 | 0.9303 | 0.8009 |
| 30 | 75 | 0.8860 | 0.7307 | 0.9284 | 0.8009 |
| 40 | 55 | 0.8815 | 0.7337 | 0.9241 | 0.8008 |
| 30 | 85 | 0.8860 | 0.7306 | 0.9285 | 0.8008 |
| 30 | 90 | 0.8860 | 0.7306 | 0.9285 | 0.8008 |
| 45 | 65 | 0.8822 | 0.7332 | 0.9250 | 0.8008 |
| 30 | 95 | 0.8860 | 0.7306 | 0.9285 | 0.8008 |
| 45 | 80 | 0.8829 | 0.7327 | 0.9257 | 0.8008 |
| 40 | 60 | 0.8831 | 0.7325 | 0.9260 | 0.8008 |
| 45 | 75 | 0.8829 | 0.7327 | 0.9257 | 0.8008 |
| 45 | 85 | 0.8830 | 0.7325 | 0.9259 | 0.8008 |
| 45 | 70 | 0.8823 | 0.7331 | 0.9249 | 0.8008 |
| 45 | 90 | 0.8831 | 0.7325 | 0.9259 | 0.8007 |
| 30 | 40 | 0.8776 | 0.7362 | 0.9184 | 0.8007 |
| 45 | 95 | 0.8830 | 0.7324 | 0.9258 | 0.8007 |
| 65 | 80 | 0.8701 | 0.7415 | 0.9117 | 0.8007 |
| 60 | 75 | 0.8737 | 0.7388 | 0.9161 | 0.8006 |
| 20 | 30 | 0.8861 | 0.7301 | 0.9284 | 0.8005 |
| 55 | 70 | 0.8737 | 0.7385 | 0.9150 | 0.8005 |
| 45 | 60 | 0.8800 | 0.7339 | 0.9227 | 0.8003 |
| 15 | 25 | 0.8880 | 0.7282 | 0.9297 | 0.8002 |
| 15 | 20 | 0.8795 | 0.7340 | 0.9192 | 0.8002 |
| 70 | 85 | 0.8700 | 0.7406 | 0.9122 | 0.8001 |
| 15 | 40 | 0.8895 | 0.7269 | 0.9314 | 0.8000 |
| 5 | 10 | 0.8961 | 0.7225 | 0.9360 | 0.8000 |
| 20 | 25 | 0.8722 | 0.7389 | 0.9105 | 0.8000 |
| 70 | 90 | 0.8703 | 0.7401 | 0.9125 | 0.7999 |
| 15 | 30 | 0.8887 | 0.7273 | 0.9304 | 0.7999 |
| 15 | 35 | 0.8893 | 0.7269 | 0.9312 | 0.7999 |

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Table A.3 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 5 | 15 | 0.8970 | 0.7218 | 0.9366 | 0.7999 |
| 5 | 20 | 0.8971 | 0.7217 | 0.9367 | 0.7999 |
| 10 | 20 | 0.8917 | 0.7252 | 0.9332 | 0.7999 |
| 5 | 40 | 0.8971 | 0.7217 | 0.9366 | 0.7999 |
| 50 | 60 | 0.8677 | 0.7419 | 0.9070 | 0.7999 |
| 15 | 45 | 0.8896 | 0.7266 | 0.9315 | 0.7999 |
| 5 | 25 | 0.8970 | 0.7217 | 0.9366 | 0.7999 |
| 5 | 45 | 0.8971 | 0.7216 | 0.9366 | 0.7999 |
| 5 | 55 | 0.8971 | 0.7216 | 0.9366 | 0.7998 |
| 5 | 50 | 0.8971 | 0.7216 | 0.9366 | 0.7998 |
| 5 | 60 | 0.8971 | 0.7216 | 0.9366 | 0.7998 |
| 5 | 30 | 0.8970 | 0.7216 | 0.9366 | 0.7998 |
| 40 | 50 | 0.8750 | 0.7366 | 0.9170 | 0.7998 |
| 5 | 90 | 0.8970 | 0.7216 | 0.9367 | 0.7998 |
| 5 | 95 | 0.8970 | 0.7216 | 0.9367 | 0.7998 |
| 5 | 80 | 0.8970 | 0.7216 | 0.9366 | 0.7998 |
| 5 | 85 | 0.8970 | 0.7216 | 0.9367 | 0.7998 |
| 5 | 75 | 0.8970 | 0.7216 | 0.9366 | 0.7998 |
| 5 | 70 | 0.8970 | 0.7216 | 0.9366 | 0.7998 |
| 70 | 95 | 0.8706 | 0.7397 | 0.9126 | 0.7998 |
| 5 | 65 | 0.8970 | 0.7216 | 0.9366 | 0.7998 |
| 5 | 35 | 0.8970 | 0.7215 | 0.9366 | 0.7998 |
| 15 | 50 | 0.8895 | 0.7265 | 0.9315 | 0.7998 |
| 10 | 30 | 0.8921 | 0.7247 | 0.9334 | 0.7997 |
| 10 | 25 | 0.8918 | 0.7249 | 0.9333 | 0.7997 |
| 15 | 55 | 0.8894 | 0.7264 | 0.9315 | 0.7997 |
| 10 | 45 | 0.8922 | 0.7245 | 0.9334 | 0.7996 |
| 10 | 40 | 0.8922 | 0.7245 | 0.9334 | 0.7996 |
| 10 | 35 | 0.8922 | 0.7245 | 0.9335 | 0.7996 |
| 10 | 95 | 0.8922 | 0.7245 | 0.9335 | 0.7996 |
| 10 | 90 | 0.8922 | 0.7245 | 0.9335 | 0.7996 |
| 10 | 80 | 0.8922 | 0.7245 | 0.9335 | 0.7996 |
| 10 | 85 | 0.8922 | 0.7245 | 0.9335 | 0.7996 |
| 15 | 90 | 0.8894 | 0.7263 | 0.9315 | 0.7996 |
| 10 | 75 | 0.8922 | 0.7245 | 0.9335 | 0.7996 |
| 10 | 70 | 0.8922 | 0.7245 | 0.9335 | 0.7996 |
| 15 | 95 | 0.8894 | 0.7263 | 0.9315 | 0.7996 |
| 15 | 85 | 0.8894 | 0.7263 | 0.9315 | 0.7996 |
| 15 | 65 | 0.8894 | 0.7263 | 0.9314 | 0.7996 |
| 15 | 60 | 0.8894 | 0.7263 | 0.9314 | 0.7996 |
| 15 | 80 | 0.8894 | 0.7263 | 0.9315 | 0.7996 |
| 15 | 70 | 0.8894 | 0.7263 | 0.9315 | 0.7996 |
| 10 | 65 | 0.8921 | 0.7245 | 0.9334 | 0.7996 |
| 15 | 75 | 0.8894 | 0.7263 | 0.9315 | 0.7996 |
| 10 | 60 | 0.8921 | 0.7245 | 0.9334 | 0.7996 |
| 10 | 55 | 0.8921 | 0.7245 | 0.9334 | 0.7996 |
| 10 | 50 | 0.8922 | 0.7244 | 0.9334 | 0.7996 |
| 10 | 15 | 0.8872 | 0.7276 | 0.9275 | 0.7995 |
| 75 | 90 | 0.8609 | 0.7460 | 0.9016 | 0.7993 |
| 75 | 85 | 0.8557 | 0.7496 | 0.8946 | 0.7992 |
| 75 | 95 | 0.8610 | 0.7452 | 0.9017 | 0.7989 |
| 55 | 65 | 0.8644 | 0.7426 | 0.9039 | 0.7989 |
| 60 | 70 | 0.8627 | 0.7429 | 0.9039 | 0.7983 |
| 45 | 55 | 0.8725 | 0.7356 | 0.9156 | 0.7982 |
| 25 | 30 | 0.8671 | 0.7393 | 0.9055 | 0.7981 |
| 30 | 35 | 0.8607 | 0.7426 | 0.8998 | 0.7973 |
| 65 | 75 | 0.8579 | 0.7432 | 0.9004 | 0.7965 |
| 35 | 40 | 0.8547 | 0.7456 | 0.8918 | 0.7964 |
| 70 | 80 | 0.8566 | 0.7441 | 0.8980 | 0.7964 |

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Table A.3 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 40 | 45 | 0.8526 | 0.7448 | 0.8922 | 0.7950 |
| 55 | 60 | 0.8392 | 0.7530 | 0.8756 | 0.7938 |
| 45 | 50 | 0.8501 | 0.7437 | 0.8892 | 0.7934 |
| 80 | 90 | 0.8423 | 0.7483 | 0.8849 | 0.7925 |
| 80 | 95 | 0.8437 | 0.7471 | 0.8864 | 0.7925 |
| 50 | 55 | 0.8435 | 0.7454 | 0.8838 | 0.7914 |
| 60 | 65 | 0.8393 | 0.7484 | 0.8793 | 0.7913 |
| 65 | 70 | 0.8328 | 0.7482 | 0.8739 | 0.7882 |
| 75 | 80 | 0.8278 | 0.7501 | 0.8688 | 0.7870 |
| 85 | 95 | 0.8198 | 0.7556 | 0.8570 | 0.7864 |
| 80 | 85 | 0.8228 | 0.7524 | 0.8639 | 0.7861 |
| 70 | 75 | 0.8259 | 0.7495 | 0.8660 | 0.7859 |
| 90 | 95 | 0.7998 | 0.7664 | 0.8337 | 0.7827 |
| 85 | 90 | 0.8071 | 0.7515 | 0.8493 | 0.7783 |

Table A.4: Trapezoids parameters tuning results for SFA dataset and combined rules.

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 5 | 5 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 10 | 10 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 15 | 15 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 20 | 20 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 25 | 25 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 30 | 30 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 35 | 35 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 40 | 40 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 45 | 45 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 50 | 50 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 55 | 55 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 60 | 60 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 65 | 65 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 70 | 70 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 75 | 75 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 80 | 80 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 85 | 85 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 90 | 90 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 95 | 95 | 0.9313 | 0.6617 | 0.9785 | 0.7737 |
| 85 | 90 | 0.8307 | 0.4534 | 0.9519 | 0.5866 |
| 70 | 75 | 0.8554 | 0.4442 | 0.9651 | 0.5848 |
| 80 | 90 | 0.8721 | 0.4385 | 0.9733 | 0.5835 |
| 50 | 55 | 0.8721 | 0.4383 | 0.9718 | 0.5834 |
| 85 | 95 | 0.8610 | 0.4411 | 0.9685 | 0.5833 |
| 80 | 95 | 0.8743 | 0.4376 | 0.9742 | 0.5833 |
| 60 | 65 | 0.8631 | 0.4403 | 0.9682 | 0.5831 |
| 75 | 90 | 0.8795 | 0.4358 | 0.9779 | 0.5828 |
| 70 | 90 | 0.8870 | 0.4337 | 0.9801 | 0.5825 |
| 75 | 95 | 0.8803 | 0.4352 | 0.9780 | 0.5825 |
| 70 | 85 | 0.8849 | 0.4340 | 0.9797 | 0.5823 |
| 70 | 95 | 0.8874 | 0.4332 | 0.9801 | 0.5822 |
| 70 | 80 | 0.8796 | 0.4349 | 0.9784 | 0.5820 |
| 60 | 70 | 0.8860 | 0.4333 | 0.9809 | 0.5819 |
| 65 | 80 | 0.8877 | 0.4326 | 0.9805 | 0.5817 |
| 55 | 60 | 0.8657 | 0.4380 | 0.9725 | 0.5816 |
| 65 | 70 | 0.8512 | 0.4416 | 0.9664 | 0.5815 |
| 60 | 75 | 0.8914 | 0.4315 | 0.9823 | 0.5815 |
| 65 | 75 | 0.8832 | 0.4334 | 0.9796 | 0.5814 |

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Table A.4 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 60 | 80 | 0.8938 | 0.4308 | 0.9826 | 0.5814 |
| 75 | 80 | 0.8375 | 0.4452 | 0.9599 | 0.5814 |
| 75 | 85 | 0.8739 | 0.4355 | 0.9768 | 0.5813 |
| 45 | 55 | 0.8956 | 0.4302 | 0.9824 | 0.5812 |
| 55 | 65 | 0.8872 | 0.4320 | 0.9811 | 0.5810 |
| 50 | 60 | 0.8888 | 0.4315 | 0.9806 | 0.5810 |
| 55 | 70 | 0.8907 | 0.4308 | 0.9817 | 0.5808 |
| 45 | 60 | 0.8991 | 0.4289 | 0.9834 | 0.5807 |
| 55 | 80 | 0.8968 | 0.4294 | 0.9830 | 0.5807 |
| 65 | 90 | 0.8913 | 0.4306 | 0.9817 | 0.5807 |
| 55 | 75 | 0.8945 | 0.4298 | 0.9828 | 0.5806 |
| 65 | 85 | 0.8902 | 0.4307 | 0.9816 | 0.5806 |
| 65 | 95 | 0.8913 | 0.4304 | 0.9818 | 0.5805 |
| 35 | 40 | 0.8897 | 0.4308 | 0.9797 | 0.5805 |
| 60 | 90 | 0.8952 | 0.4293 | 0.9828 | 0.5803 |
| 60 | 85 | 0.8949 | 0.4294 | 0.9827 | 0.5803 |
| 60 | 95 | 0.8951 | 0.4292 | 0.9828 | 0.5802 |
| 55 | 90 | 0.8982 | 0.4284 | 0.9833 | 0.5801 |
| 45 | 65 | 0.9000 | 0.4279 | 0.9836 | 0.5800 |
| 55 | 85 | 0.8977 | 0.4284 | 0.9832 | 0.5800 |
| 50 | 80 | 0.8997 | 0.4279 | 0.9837 | 0.5799 |
| 40 | 45 | 0.8885 | 0.4304 | 0.9802 | 0.5799 |
| 55 | 95 | 0.8982 | 0.4282 | 0.9833 | 0.5799 |
| 30 | 35 | 0.8984 | 0.4281 | 0.9821 | 0.5799 |
| 45 | 75 | 0.9035 | 0.4270 | 0.9844 | 0.5799 |
| 50 | 75 | 0.8985 | 0.4280 | 0.9836 | 0.5799 |
| 40 | 55 | 0.9000 | 0.4277 | 0.9837 | 0.5798 |
| 45 | 70 | 0.9011 | 0.4274 | 0.9838 | 0.5798 |
| 45 | 80 | 0.9039 | 0.4268 | 0.9845 | 0.5798 |
| 35 | 45 | 0.9005 | 0.4275 | 0.9836 | 0.5798 |
| 50 | 70 | 0.8953 | 0.4286 | 0.9827 | 0.5797 |
| 45 | 50 | 0.8804 | 0.4321 | 0.9784 | 0.5797 |
| 40 | 50 | 0.8982 | 0.4279 | 0.9835 | 0.5796 |
| 50 | 65 | 0.8919 | 0.4291 | 0.9822 | 0.5795 |
| 35 | 50 | 0.9039 | 0.4263 | 0.9844 | 0.5794 |
| 40 | 60 | 0.9017 | 0.4267 | 0.9841 | 0.5793 |
| 45 | 90 | 0.9046 | 0.4259 | 0.9846 | 0.5792 |
| 50 | 90 | 0.9006 | 0.4268 | 0.9839 | 0.5791 |
| 45 | 85 | 0.9045 | 0.4259 | 0.9846 | 0.5791 |
| 50 | 85 | 0.9002 | 0.4268 | 0.9838 | 0.5791 |
| 45 | 95 | 0.9046 | 0.4258 | 0.9846 | 0.5790 |
| 50 | 95 | 0.9006 | 0.4267 | 0.9839 | 0.5790 |
| 30 | 40 | 0.9054 | 0.4255 | 0.9842 | 0.5790 |
| 40 | 65 | 0.9029 | 0.4260 | 0.9843 | 0.5789 |
| 35 | 55 | 0.9050 | 0.4255 | 0.9846 | 0.5789 |
| 40 | 70 | 0.9038 | 0.4256 | 0.9845 | 0.5787 |
| 40 | 75 | 0.9051 | 0.4254 | 0.9848 | 0.5787 |
| 25 | 35 | 0.9103 | 0.4242 | 0.9855 | 0.5787 |
| 25 | 30 | 0.9049 | 0.4253 | 0.9844 | 0.5786 |
| 40 | 80 | 0.9053 | 0.4252 | 0.9849 | 0.5786 |
| 35 | 60 | 0.9065 | 0.4249 | 0.9849 | 0.5786 |
| 30 | 45 | 0.9069 | 0.4247 | 0.9848 | 0.5785 |
| 30 | 50 | 0.9078 | 0.4243 | 0.9852 | 0.5783 |
| 35 | 65 | 0.9072 | 0.4243 | 0.9850 | 0.5781 |
| 40 | 90 | 0.9061 | 0.4244 | 0.9851 | 0.5781 |
| 25 | 40 | 0.9113 | 0.4233 | 0.9857 | 0.5781 |
| 40 | 85 | 0.9057 | 0.4244 | 0.9850 | 0.5780 |
| 30 | 55 | 0.9086 | 0.4238 | 0.9855 | 0.5780 |
| 35 | 75 | 0.9083 | 0.4238 | 0.9853 | 0.5780 |

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Table A.4 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|------|------|-----------|--------|-------------|-----------|
| 35 | 70 | 0.9077 | 0.4239 | 0.9851 | 0.5779 |
| 40 | 95 | 0.9061 | 0.4243 | 0.9851 | 0.5779 |
| 35 | 80 | 0.9084 | 0.4237 | 0.9853 | 0.5779 |
| 30 | 60 | 0.9098 | 0.4234 | 0.9857 | 0.5778 |
| 30 | 65 | 0.9101 | 0.4230 | 0.9858 | 0.5776 |
| 35 | 90 | 0.9093 | 0.4231 | 0.9855 | 0.5775 |
| 30 | 70 | 0.9101 | 0.4229 | 0.9859 | 0.5774 |
| 30 | 75 | 0.9106 | 0.4227 | 0.9860 | 0.5774 |
| 35 | 85 | 0.9089 | 0.4231 | 0.9854 | 0.5774 |
| 35 | 95 | 0.9093 | 0.4229 | 0.9855 | 0.5773 |
| 25 | 45 | 0.9119 | 0.4223 | 0.9860 | 0.5773 |
| 30 | 80 | 0.9106 | 0.4226 | 0.9860 | 0.5773 |
| 25 | 50 | 0.9124 | 0.4220 | 0.9861 | 0.5771 |
| 20 | 25 | 0.9111 | 0.4220 | 0.9854 | 0.5768 |
| 30 | 90 | 0.9109 | 0.4219 | 0.9861 | 0.5767 |
| 20 | 30 | 0.9156 | 0.4209 | 0.9865 | 0.5767 |
| 25 | 55 | 0.9132 | 0.4214 | 0.9865 | 0.5767 |
| 30 | 85 | 0.9107 | 0.4219 | 0.9860 | 0.5767 |
| 30 | 95 | 0.9109 | 0.4218 | 0.9861 | 0.5766 |
| 25 | 60 | 0.9138 | 0.4211 | 0.9866 | 0.5765 |
| 25 | 65 | 0.9140 | 0.4207 | 0.9866 | 0.5762 |
| 25 | 70 | 0.9139 | 0.4205 | 0.9867 | 0.5760 |
| 25 | 75 | 0.9144 | 0.4204 | 0.9867 | 0.5760 |
| 25 | 80 | 0.9144 | 0.4203 | 0.9867 | 0.5759 |
| 20 | 35 | 0.9169 | 0.4194 | 0.9869 | 0.5755 |
| 25 | 90 | 0.9147 | 0.4198 | 0.9868 | 0.5754 |
| 25 | 95 | 0.9147 | 0.4197 | 0.9868 | 0.5754 |
| 80 | 85 | 0.8375 | 0.4382 | 0.9608 | 0.5753 |
| 25 | 85 | 0.9144 | 0.4197 | 0.9868 | 0.5753 |
| 20 | 40 | 0.9172 | 0.4190 | 0.9870 | 0.5752 |
| 20 | 45 | 0.9170 | 0.4184 | 0.9870 | 0.5746 |
| 20 | 50 | 0.9170 | 0.4182 | 0.9871 | 0.5745 |
| 20 | 55 | 0.9173 | 0.4178 | 0.9872 | 0.5741 |
| 20 | 60 | 0.9175 | 0.4175 | 0.9872 | 0.5739 |
| 20 | 65 | 0.9178 | 0.4172 | 0.9873 | 0.5737 |
| 20 | 70 | 0.9178 | 0.4170 | 0.9874 | 0.5735 |
| 20 | 75 | 0.9179 | 0.4169 | 0.9874 | 0.5734 |
| 20 | 80 | 0.9179 | 0.4168 | 0.9874 | 0.5733 |
| 20 | 90 | 0.9179 | 0.4164 | 0.9874 | 0.5729 |
| 20 | 85 | 0.9179 | 0.4163 | 0.9874 | 0.5728 |
| 20 | 95 | 0.9179 | 0.4163 | 0.9874 | 0.5728 |
| 15 | 20 | 0.9162 | 0.4157 | 0.9859 | 0.5719 |
| 15 | 25 | 0.9186 | 0.4146 | 0.9867 | 0.5713 |
| 15 | 30 | 0.9206 | 0.4140 | 0.9872 | 0.5711 |
| 15 | 35 | 0.9213 | 0.4131 | 0.9876 | 0.5704 |
| 15 | 40 | 0.9213 | 0.4130 | 0.9876 | 0.5703 |
| 15 | 45 | 0.9211 | 0.4125 | 0.9876 | 0.5698 |
| 15 | 50 | 0.9211 | 0.4124 | 0.9877 | 0.5697 |
| 15 | 55 | 0.9212 | 0.4120 | 0.9878 | 0.5693 |
| 15 | 60 | 0.9211 | 0.4117 | 0.9878 | 0.5690 |
| 15 | 65 | 0.9214 | 0.4114 | 0.9879 | 0.5688 |
| 15 | 75 | 0.9217 | 0.4111 | 0.9880 | 0.5686 |
| 15 | 70 | 0.9213 | 0.4112 | 0.9879 | 0.5686 |
| 15 | 80 | 0.9217 | 0.4111 | 0.9880 | 0.5686 |
| 15 | 90 | 0.9217 | 0.4107 | 0.9880 | 0.5682 |
| 15 | 85 | 0.9218 | 0.4106 | 0.9880 | 0.5682 |
| 15 | 95 | 0.9217 | 0.4106 | 0.9880 | 0.5681 |
| 10 | 15 | 0.9197 | 0.4092 | 0.9870 | 0.5664 |
| 10 | 20 | 0.9218 | 0.4071 | 0.9873 | 0.5648 |

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Table A.4 – continued from previous page

| Pmin | Pmax | Precision | Recall | Specificity | F-measure |
|-------------|-------------|------------------|---------------|--------------------|------------------|
| 10 | 25 | 0.9223 | 0.4066 | 0.9875 | 0.5644 |
| 10 | 30 | 0.9236 | 0.4060 | 0.9879 | 0.5641 |
| 10 | 35 | 0.9242 | 0.4052 | 0.9882 | 0.5634 |
| 10 | 40 | 0.9243 | 0.4052 | 0.9883 | 0.5634 |
| 10 | 45 | 0.9241 | 0.4049 | 0.9883 | 0.5631 |
| 10 | 50 | 0.9240 | 0.4048 | 0.9883 | 0.5630 |
| 90 | 95 | 0.8103 | 0.4311 | 0.9542 | 0.5628 |
| 10 | 55 | 0.9240 | 0.4045 | 0.9884 | 0.5627 |
| 10 | 60 | 0.9239 | 0.4042 | 0.9884 | 0.5624 |
| 10 | 65 | 0.9242 | 0.4039 | 0.9885 | 0.5621 |
| 10 | 70 | 0.9243 | 0.4038 | 0.9885 | 0.5621 |
| 10 | 75 | 0.9243 | 0.4037 | 0.9885 | 0.5620 |
| 10 | 80 | 0.9243 | 0.4037 | 0.9886 | 0.5619 |
| 10 | 85 | 0.9248 | 0.4032 | 0.9886 | 0.5615 |
| 10 | 90 | 0.9247 | 0.4031 | 0.9886 | 0.5615 |
| 10 | 95 | 0.9246 | 0.4030 | 0.9886 | 0.5614 |
| 5 | 10 | 0.9241 | 0.4006 | 0.9873 | 0.5589 |
| 5 | 15 | 0.9260 | 0.3982 | 0.9878 | 0.5569 |
| 5 | 20 | 0.9269 | 0.3972 | 0.9881 | 0.5561 |
| 5 | 25 | 0.9267 | 0.3968 | 0.9882 | 0.5557 |
| 5 | 50 | 0.9282 | 0.3961 | 0.9889 | 0.5553 |
| 5 | 30 | 0.9269 | 0.3963 | 0.9884 | 0.5553 |
| 5 | 60 | 0.9284 | 0.3960 | 0.9890 | 0.5552 |
| 5 | 90 | 0.9284 | 0.3960 | 0.9890 | 0.5552 |
| 5 | 55 | 0.9284 | 0.3960 | 0.9890 | 0.5552 |
| 5 | 40 | 0.9275 | 0.3962 | 0.9887 | 0.5552 |
| 5 | 85 | 0.9284 | 0.3960 | 0.9890 | 0.5552 |
| 5 | 45 | 0.9280 | 0.3961 | 0.9889 | 0.5552 |
| 5 | 95 | 0.9284 | 0.3960 | 0.9890 | 0.5552 |
| 5 | 65 | 0.9283 | 0.3960 | 0.9890 | 0.5551 |
| 5 | 70 | 0.9284 | 0.3959 | 0.9890 | 0.5551 |
| 5 | 80 | 0.9283 | 0.3959 | 0.9890 | 0.5551 |
| 5 | 75 | 0.9284 | 0.3959 | 0.9890 | 0.5551 |
| 5 | 35 | 0.9274 | 0.3960 | 0.9887 | 0.5550 |

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