Received November 7, 2019, accepted December 16, 2019, date of publication January 9, 2020, date of current version January 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2019.2962783

Uniformity Evaluation of Temperature Field in an Oven Based on Image Processing

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This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFC211500, and in part by the Seed Foundation of Innovation and Creation for Graduate Students in Northwestern Polytechnical University under Grant ZZ2019193.

ABSTRACT Non-uniform temperature distributions in ovens affect the quality of baked goods and raise concerns regarding food safety. Traditional research on oven performance focuses on the heating mechanisms in simulated ovens and does not involve quantitative analysis of baked goods. This study proposes a model for calculating the uniformity of baked goods based on image processing technology, to quantitatively assess the distribution uniformity of different baked states and digitally express the internal temperature field distribution in the oven. First, the image of the baked goods is captured using a digital camera. Then, it is preprocessed to obtain an image containing only the region showing the baked goods. Subsequently, the simple linear iterative clustering segmentation algorithm is employed to extract the baked states. Finally, a meshing model is applied to calculate the distribution variance of each baked state, and the evaluation index describing the uniformity of the baked goods image is obtained by normalizing the variance in the distribution. The simple linear iterative clustering segmentation algorithm expresses the color features of acquired baked goods images in the form of superpixels. By determining the distribution and proportion of different baked states, the proposed method can qualitatively and quantitatively reflect the spatial distribution of the temperature fields inside the oven corresponding to the baked goods image. This provides a strong basis for further evaluation of the heat distribution field inside the oven.

INDEX TERMS Image processing, meshing model, oven temperature field, simple linear iterative clustering, uniformity evaluation.

I. INTRODUCTION

Ovens have gained popularity in domestic use and are increasingly used for a variety of industrial applications. Food baking is a food processing technique in which series of complex physical, chemical, and biochemical changes take place simultaneously in the given product. Freshly baked goods has pleasant aroma, golden brown crust with fine porous structure [1]. In baked-goods-making, baking process is one of the key steps to produce the final product qualities including texture, color and flavor, as a result of several thermal reactions [2]. The quality of baked goods varies during baking due to the variation of baking conditions [3]. Baking conditions inside the oven are closely related to the temperature field inside the oven. The uniformity of the temperature distribution inside the oven is one of the important indexes for the performance evaluation of the oven, and also the important reason for the uniformity of the baking states of the baked goods. A mathematical model has been developed to analyze the uniformity of baking states distribution on the surface of baked goods to reflect the uniformity of temperature field inside the oven, so as to provide a reliable basis for optimizing the technological conditions of the oven. The characteristics of temperature distribution in different ovens are quite different, and the causes of uneven temperature distribution are complicated. Existing research on oven temperature field includes experimental studies and computational fluid dynamics (CFD) numerical simulations. Verboven et al. established a CFD model including a continuity equation, momentum equation, energy equation, and standard $k - \varepsilon$ model to simulate the temperature distribution in a forced convection oven and found that the actual

The associate editor coordinating the review of this manuscript and approving it for publication was Feng Shao.

temperature in the cavity is consistent with the simulated average temperature [4]. Smolka et al. established a CFD simulation model with a heat transfer mode, temperature-related air characteristics, and a heat transfer system of the external cavity and analyzed the flow and heat transfer process in a forced convection oven [5]. The simulation results were highly consistent with the experimental data. Chhanwal et al. employed the discrete transmission radiation model (DTRM), surface radiation model (S2S), and the discrete coordinate radiation model (DO), all of which have high accuracy [6]. As experimental studies are susceptible to test conditions and procedures, the premise of numerical simulations is to establish a simulation model that matches the reality. In addition, research on oven temperature distribution characteristics focuses only on the measurement and prediction of a specific point of the oven internal test temperature. The effect of oven internal temperature on the quality of baked goods is not reflected in these studies.

With the development of image processing technology, image processing-based uniformity detection methods have been increasingly used in the industry. Fang et al. proposed a nonwoven evenness detection method based on digital image processing [7]. After image segmentation, the fiber coverage rate was calculated, and the variation coefficient of the uniformity evaluation was obtained. Compared with the traditional weighing methods, the efficiency of the image analysis method is increased by 50 times. Huang et al. used digital image processing to study the distribution of the morphological characteristics of aggregates on the surface of an asphalt mixture, and proposed a segregation calculation and discrimination method in the paving process to monitor the uniformity of the asphalt pavement in real time [8]. Zheng et al. established a method to evaluate the uniformity of tobacco feeding based on image processing [9]. Their results effectively represent the improvement or deterioration of the overall feeding process. Feng et al. designed a set of automatic monitoring systems of glass uniformity based on image processing to detect the uniformity of glass conveniently, accurately, and quickly in the glass production process [10]. These studies showed that image processing technology has certain advantages in the applications of object uniformity detection.

Baked goods exhibit a variety of baked states. The uniformity of the distribution of different baked states should be considered in the uniformity evaluation of the baked goods image. Therefore, different baked states should be extracted based on the baked goods image. Image segmentation refers to the process of dividing an image into different regions according to certain similarity criteria. Traditional image segmentation methods include the threshold, boundary detection, and region methods [11]–[13]. The clustering method in machine learning can also be used to solve the image segmentation problem. The mean shift algorithm was first proposed by Fukunaga *et al.* [14]. Cheng et al. defined the kernel function and weight coefficient, which made the mean shift algorithm widely used [15]. Achanta et al. proposed the simple linear iterative clustering (SLIC) algorithm in 2010 [16]. In 2012, Schick et al. ensured the integrity of the superpixel after segmentation and introduced the parameters to control the compactness of superpixel generation [17]. In recent years, SLIC image segmentation has been widely used in industrial production activities. Fang et al. proposed a method of breast cancer classification based on SLIC ultrasound images [18]. The experimental accuracy was as high as 88%, and the sensitivity was 92.05%. Sethi et al. proposed a novel segmentation-based underwater image enhancement method, which used SLIC to segment the image [19]. Bath et al. proposed a method based on Hough transform and SLIC segmentation, which is very reliable for crop line and weed detection [20]. This study proposes an improved SLIC segmentation method to evaluate the uniformity of baked goods images.

Currently, the uniformity evaluation of baked goods images relies on the evaluation method proposed by the VDE Testing and Certification Institute in Germany (DIN 55350-11) [21]. This method can obtain the image of the small round biscuits cooked. According to IEC 60350, a single round cookie is divided into 13 parts [22]. The color of each part of the small round biscuit in the image is compared with the standard color card, and the cookie surface color is divided into seven grades. In this manner, the color distribution uniformity on the surface of the small round biscuit was determined qualitatively. Furthermore, these observations reflect the uniformity of the temperature field inside the oven. However, this method does not quantitatively assess the color uniformity in baked goods images. And, the color division method based on the standard color card is prone to artificial judgment error. The size of baked goods will change during the baking process, so it is not easy to control their size. As this method integrates the size characteristics of baked goods, there will be some errors in the evaluation process. In this study, we define the quality evaluation of baked goods using the same color feature standard and apply the improved SLIC segmentation method to extract different baked states with the aim to quantitatively evaluate the influence of oven temperature distribution on the quality of baked goods.

In this study, the baked goods image captured by the camera was preprocessed, and the color characteristics of the image were analyzed. Different baked states were extracted from the image using the image segmentation method. The distribution of baked states in different ovens was qualitatively and quantitatively analyzed under the same color characteristics analysis to obtain a strong basis for improving the uniformity of the oven temperature field.

The remainder of this paper is organized as follows: Section II describes the proposed calculation model regarding surface distribution uniformity of the baked goods image. Section III introduces the acquisition, preprocessing, color feature extraction, image segmentation model, and calculation of the surface distribution uniformity of baked goods images. Section IV introduces the results of the image uniformity experiments and briefly describes the VDE research method. In addition, Section IV presents the discussion of the

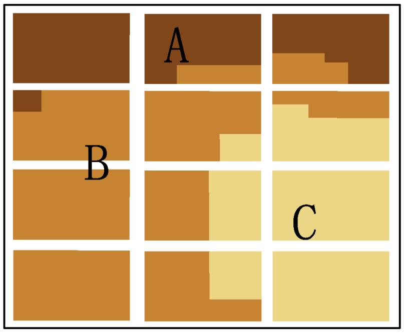


FIGURE 1. Baked goods image model. A represents the region of the burnt state; B represents the region of the moderately baked state; and C represents the region of the uncooked state.

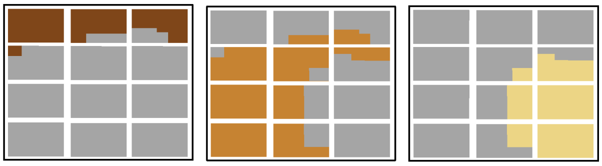


FIGURE 2. Color feature distribution model of different baking states. (a), (b), and (c) represent the color characteristic distribution of three baking states in terms of the image model of the baked goods.

experimental results. Section V provides a summary of the results.

II. CALCULATION MODEL OF BAKED GOODS IMAGE UNIFORMITY

A. DESCRIPTION OF BAKED GOODS IMAGE MODEL

There are three types of baked goods: burnt, moderately cooked, and uncooked. The image model of baked goods is shown in Fig. 1.

The baked goods' uniformity is related to the proportion and position distribution of these three baked states. If the uniformity of the baked goods is satisfactory, then all three baked states should be uniformly distributed; otherwise, at least one baked state is not evenly distributed. Therefore, to evaluate the uniformity of a baked goods image, the uniformity of each baked state distribution should be considered.

To evaluate image uniformity, the uniformity of the color feature distribution for each baked state needs to be evaluated separately. Subsequently, we need to normalize the uniformity evaluation values of the three baked states to obtain the uniformity evaluation index of the baked goods image.

B. UNIFORMITY CALCULATION MODEL OF SINGLE BAKED STATE DISTRIBUTION

Variance is one of the most commonly used measures of dispersion. A larger density variance of an object indicates a more uneven density distribution. Hence, the variance of local density can be used to describe the uniformity of particle distribution. In this study, the meshing approach for computing the distribution variance was used to evaluate the uniformity of a single baked state distribution image.

Taking the moderate baked state as an example, the uniformity calculation model of the single baked state distribution was analyzed. The distribution uniformity calculation model results of the burnt and uncooked states were consistent with that of the moderate baked state. The hypothesis of the uniformity evaluation calculation model of the single baked state distribution can be summarized as follows.

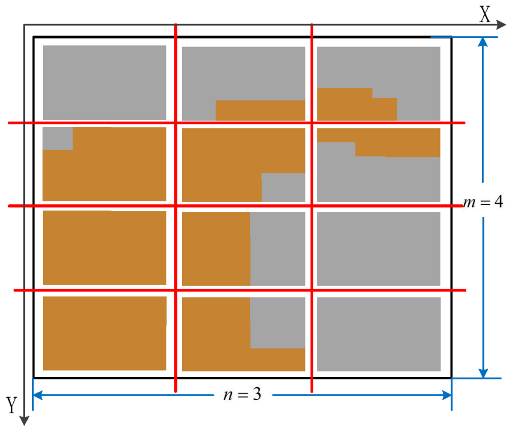


FIGURE 3. Meshing model of moderately cooked state.

1) Assume that the baked goods and the baking tray are rectangular.
2) The total number of baked goods is $m \times n$, and the baking tray is divided into $m \times n$ grids. The area of the i-th moderate baked state in the grid is $s_M[i]$, and the total area of the moderate baked state is S_M.

The model is shown in Fig. 3. The area of the i-th grid block with the moderate baked state is $s_M[i]$, the area of the moderate baked state in the entire baked goods image is $S_M = \sum_{i=1}^{m\times n} S_M[i]$, and the average area of the moderate baked state is $\overline{S} = \frac{S_M}{m\times n}$; which depicts the area evenly distributed in each grid in the moderate state. Then, the variance between the local area of the moderate state and the total area of the moderate state in each grid is expressed by Eq. 1.

$$\sigma_M^2 = \frac{1}{m \times n}\sum_{i=1}^{m\times n}(s_M[i] - \overline{S_M})^2. \tag{1}$$

The variance can be used to evaluate the uniformity of the baked state distribution. Larger variance indicates more uneven baked state distribution; smaller variance indicates more uniform baked state distribution.

C. CALCULATION MODEL OF IMAGE UNIFORMITY OF BAKED GOODS

The distribution variances of the burnt state, moderate baked state, and uncooked state are σ_B^2, σ_M^2, and σ_U^2 respectively. For a baked goods image, the uniformity evaluation indices should be normalized. For the uniformity evaluation of an image, not only the position distribution of different baked states, but also their proportion should be considered. Therefore, in this study, we chose the proportions of different baked states to weight the distribution variances and then obtain the uniformity evaluation index of the baked goods images.

Suppose that the color proportions in the burnt state, moderate baked state, and the uncooked state shown in Fig. 1 are P_B, P_M, and P_U resectively (Eq. 2).

$$P_B = \frac{\sum Pixel(L_i == L_B)}{\sum Pixel} \times 100\%.$$
$$P_M = \frac{\sum Pixel(L_i == L_M)}{\sum Pixel} \times 100\%.$$
$$P_U = \frac{\sum Pixel(L_i == L_U)}{\sum Pixel} \times 100\%. \qquad (2)$$

where L_i represents the color feature value of the i-th point of the baked goods image, and $\sum Pixel$ represents the sum of the pixel points of the baked goods image.

Then, the uniformity evaluation index VoU can be calculated using Eq. 3.

$$VoU = \frac{1}{100}(P_B \times \sigma_B^2 + P_M \times \sigma_M^2 + P_U \times \sigma_U^2). \qquad (3)$$

III. EXAMPLE OF BAKED GOODS IMAGE UNIFORMITY CALCULATION

According to the control variable method, it is necessary to ensure that baked goods have the same ingredients and similar shapes. The baked good used in this study is toast, and the baked state of the toast bread is described as follows: if it is dark yellow, the toast is burnt; if it is moderate yellow, the toast is moderately baked; if it is light yellow, the toast is uncooked.

A. IMAGE ACQUISITION AND PREPROCESSING OF BAKED GOODS

A digital image is the digitization of the spatial position and brightness of an object and can be viewed as a matrix or a two-dimensional array [23]. To reduce or avoid information errors in the original image, it is necessary to standardize image acquisition. During the acquisition of the baked goods images using a camera, there should be no other light interference in the image capturing area. The lens plane of the camera should be parallel to the baking tray. Meanwhile, the camera parameters and the relative distance between the camera and the baking tray should be recorded to ensure that all images are shot under the same conditions. A digital baked goods image is shown in Fig. 4.

As the working conditions of high-definition digital cameras are affected by many factors. Noise is generated in various situations such as image acquisition, information output, and image format compression, affecting the accuracy of the image analysis. Therefore, it is necessary to preprocess the baked goods images before analysis.

FIGURE 4. Digital image of baked goods.

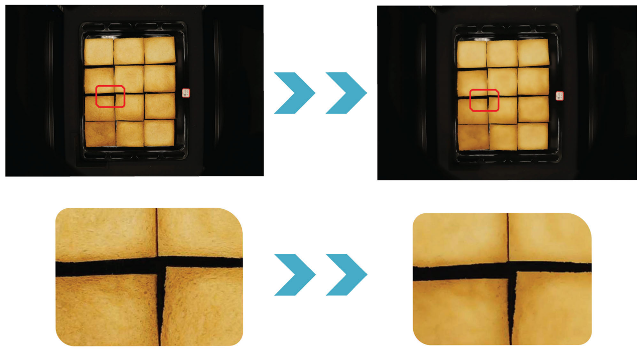


FIGURE 5. Comparison of baked goods image before and after bilateral filtering.

Bilateral filtering algorithms can effectively denoise and protect the edge information of an image [23]. The kernel function of bilateral filtering is the comprehensive result of the spatial domain kernel and the pixel domain kernel. In the flat area of the image, the corresponding pixel domain weight is close to 1, and the spatial domain weight plays a major role; in the edge area of the image, the pixel domain weight becomes larger, thus maintaining the edge information [24] (Eq. 4), as shown at the bottom of this page.

where I_D is the noise intensity of the pixel point, $I(i,j)$ is the value of the image (i,j) pixel, $I(k,l)$ is the value of the image (k,l) pixel, σ_r^2 is the spatial domain smoothing factor, and σ_d^2 is the pixel domain smoothing factor. In this study, the standard deviation of the color space is 50, and that of coordinate space is 25. Fig. 5 is the filter comparison diagram of the baked goods image.

The baked goods image before filtering is noisy, while the baked goods image after filtering is smooth and retains the edge information of baked goods. To improve the operation efficiency, the image background must be removed. After filtering, the image background can be effectively removed

$$I_D(i,j) = \frac{\sum_{k,l} I(k,l) \times exp(-\frac{(i-k)^2+(j-l)^2}{2\sigma_d^2}) \times exp(-\frac{||(i-k)^2+(j-l)||^2}{2\sigma_r^2})}{\sum_{k,l} exp(-\frac{(i-k)^2+(j-l)^2}{2\sigma_d^2}) \times exp(-\frac{||(i-k)^2+(j-l)||^2}{2\sigma_r^2})}. \qquad (4)$$

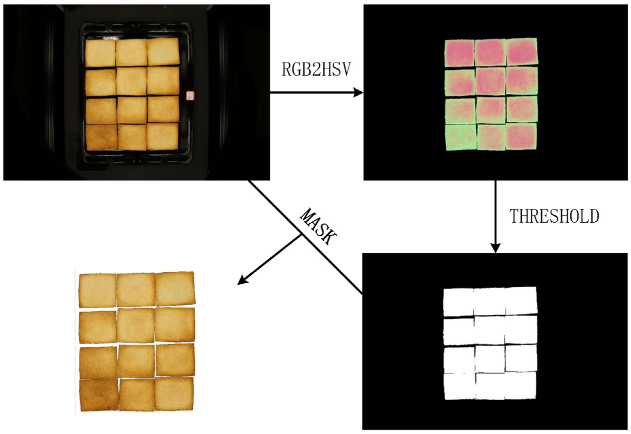


FIGURE 6. Schematic diagram of background removal of an image.

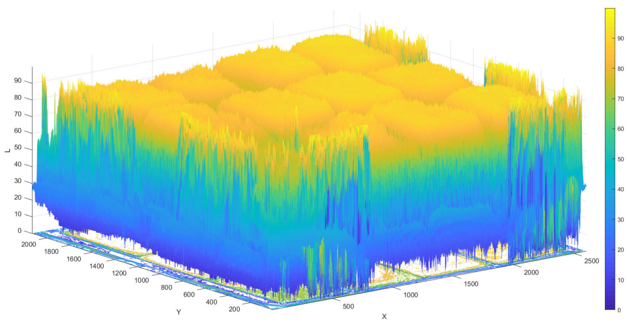


FIGURE 7. 3D view of the L value of the baked goods image.

by color space conversion, threshold extraction, connected area partition, and other preprocessing steps to obtain a pure image, as shown in Fig. 6.

B. FEATURE ANALYSIS AND EXTRACTION

In the RGB color space, the color of the baked goods image is mixed with three colors of red (R), green (G), and blue (B) [26]. Thus, a single indicator that can characterize the baked state of the baked goods cannot be obtained. Compared to the RGB color space, CIELab is a device-independent color space based on physiological features [27]. The L component in the CIELab color space is used to represent the brightness of the pixel; the a component represents a range from red to green; the b component represents a range from yellow to blue. The preprocessed baked goods image is subjected to color space conversion to obtain a baked goods image in the CIELab color space. Fig. 8 illustrates a 3D view of the L value of the baked goods image.

Compared with the original baked goods image, the L value can reflect the baked state of the baked goods image. If the baked goods is burnt, i.e., if the color area is dark yellow, the L value of the corresponding area is low; if the baked goods is uncooked, i.e., if the color area is light yellow, the L value of the corresponding area is high. Therefore, the L value can be used as the color feature of the baked goods image. The obtained baked goods images were professionally evaluated and tested several times to get a comprehensive

TABLE 1. L values in different baking states.

Baking state	L value
Burnt	$L \leq 45$
Moderate	$45 < L \leq 70$
Uncooked	$70 < L$

FIGURE 8. Color characterization of different baked states.

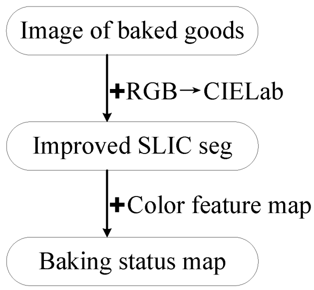


FIGURE 9. Algorithm processing flow of baked goods image.

evaluation of different baking states. We summarize the L values corresponding to different baking states in Table 1.

The color characterization corresponding to different baked states is given in Fig. 8, where A, B, and C represent the color of the burnt state, moderate baked state, and uncooked state, respectively.

C. BAKED GOODS IMAGE PROCESSING BASED ON IMPROVED SLIC SEGMENTATION ALGORITHM

In this study, an improved SLIC segmentation algorithm was proposed based on the color characteristics of the baked goods image. Fig. 9 shows the specific algorithm process flow.

SLIC is an extension of the K-means clustering algorithm. It is a simple and efficient method to build superpixels. First, the RGB color space image is transformed into the CIELab color space. Then, the color feature vectors and space coordinate vectors are comprehensively analyzed to construct the distance measurement standard, and each pixel of the image is locally clustered [25].

In this study, we developed an improved SLIC segmentation algorithm combined with the color features. In the process of image segmentation, only the color feature extracted in Section III-B was considered from the entire color space. The specific implementation steps of the improved SLIC segmentation algorithm are as follows.

Step 1: Initialize seed points. Seed points are evenly distributed in the image according to the set number of superpixels. Suppose that the image has N pixels and pre-divides K into approximately sized superpixels, then the size of each super pixel is $\frac{N}{K}$, and the step size of seed point is $S = \sqrt{\frac{N}{K}}$.

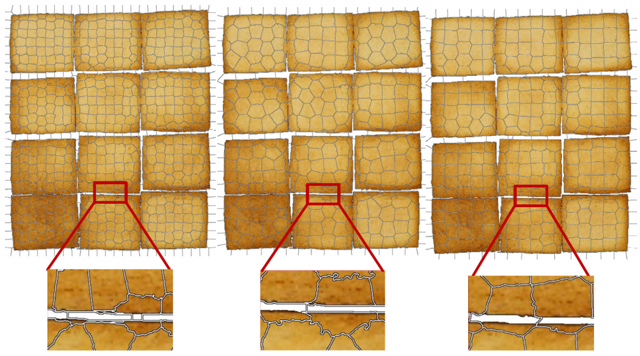


FIGURE 10. Contrast map of improved SLIC results. (a), (b), and (c) demonstrate the experimental results of $K = 800$, $m = 25$; $K = 400$, $m = 25$; and $K = 400$, $m = 50$, respectively.

Step 2: Reselect the new seed point within the σ neighborhood of the previous seed point.

Step 3: Label. A class label is assigned to the pixel within the neighborhood of each seed point, and the pixel search range is limited to $2S \times 2S$.

Step 4: Calculate distance metrics. Calculate the distance between each pixel point and its seed point and define the distance D calculation method as shown in Eq. 5.

$$D = \sqrt{\frac{(L_j - L_i)^2}{m^2} + \frac{(x_j - x_i)^2 + (y_j - y_i)^2}{S^2}} \tag{5}$$

where L_i is the L component value of the i-th pixel, (x, y) is the coordinate value of the i-th pixel, and m is used to weigh the influence of color similarity and spatial proximity. Fig. 10 shows the contrast of baked goods images processed by the improved SLIC segmentation algorithm under different parameters

Larger K values indicate that more superpixel blocks will be segmented. If K is too large, some unnecessary superpixel segmentation will be generated. Larger m values lead to a more compact superpixel block, whereas smaller m values enable better fitting of the edge of the super-pixel block to the image edge. In this study, $K = 400$ and were selected as the parameters of the improved SLIC segmentation algorithm.

Is, the more superpixel blocks will be segmented, and if it is too large, some unnecessary superpixel segmentation will be generated; the larger the m value is, the more compact the superpixel block is; the smaller the m value is, the more the edge of the superpixel block fits the image edge. In this study, $K = 400$ and $m = 25$ were selected as the parameters of the improved SLIC segmentation algorithm.

Step 5: Iteratively optimize until error convergence.

Step 6: Enhance connectivity. After the steps above, the size of the superpixel may be too small, and a single superpixel may be cut into multiple discrete superpixels. Thus, the connectivity needs to be enhanced.

The improved SLIC segmentation algorithm was used to generate compact and nearly uniform super-pixels, which reduced the linear complexity of pixels. After the improved SLIC segmentation of the baked goods image was applied, the contours of different baked states were obtained, which are in line with observations by the human eye. Based on the color representation diagrams given in Fig. 8, Fig. 10(b) can be used to visually express the baking status diagram, as shown in Fig.11. Fig. 11 directly reflects the distribution of different baked states, and the proportion of different baked states is calculated statistically (Table 2).

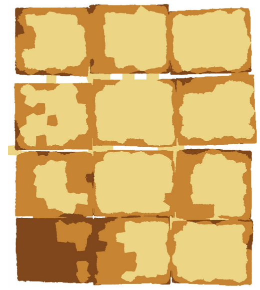


FIGURE 11. Baked states in baked goods image.

TABLE 2. Proportion of quantity in different baking states.

Baking state	Proportion(%)
Burnt (P_B)	5.85
Moderate (P_M)	43.34
Uncooked (P_U)	50.81

D. CALCULATION OF UNIFORMITY EVALUATION VALUE OF BAKED GOODS IMAGE

The baked goods image was preliminarily recorded to obtain a pure baked goods area image (Fig. 6). Then, the color feature analysis was performed on the image (Fig. 7). Finally, image segmentation was carried out based on the improved SLIC segmentation algorithm (Fig. 10). The distribution of different baked states was further characterized (Fig. 11), and their corresponding proportions were obtained (Table 2). In Section II, the distribution variances of different baked states were calculated using the meshing model, and then they were normalized to obtain the evaluation value of image uniformity.

In this study, a toast arranged in four rows and three columns was selected to cover the entire baking tray. Therefore, the grid division of the baked goods image should be 4×3, such that there is a piece of toast in each grid block. Fig. 12 is the representative diagram of the meshing model of Fig. 11.

The distribution variances of different baked states were calculated based on the single baked state distribution uniformity model proposed in Section II-B (Table 3).

The evaluation value of uniformity (VoU) of the baked goods was obtained by combining the data in Tables 2 and 3. In Eq. 6, 16.80 is the evaluation value of uniformity of the baked goods image in Fig. 4.

$$\begin{aligned} VoU &= \frac{1}{100}(P_B \times \sigma_B^2 + P_M \times \sigma_M^2 + P_U \times \sigma_U^2) \\ &= 16.80 \end{aligned} \tag{6}$$

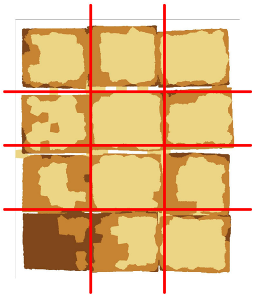


FIGURE 12. Meshing of baking state diagram.

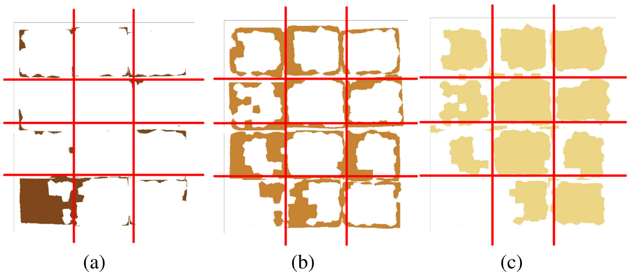


FIGURE 13. Meshing of different baking states. (a), (b), and (c) represent the grid division diagrams of three different baking states: burnt, moderately baked, and uncooked, respectively.

TABLE 3. Distribution variance of different baked states.

Baking state	Distribution variance
Burnt (σ_B^2)	4.16
Moderate (σ_M^2)	16.91
Uncooked (σ_U^2)	18.16

IV. RESULTS AND DISCUSSION

The original baked goods image was preprocessed to extract the pure baked goods region image. The color feature of the baked goods image was analyzed, and the baked goods states was determined. The improved SLIC segmentation algorithm was used to segment and extract different baked states. The evenness of the baked goods image was calculated using the proposed evenness evaluation model, and the distribution uniformity of the temperature field inside the oven was further expressed quantitatively.

In this study, two groups of comparative experiments were conducted: The proposed uniformity evaluation model was compared with the German VDE evaluation method, and multiple comparative experiments were conducted subsequently.

A. GERMAN VDE EVALUATION METHOD

The evaluation method of DIN 55350-11 proposed by the German VDE Testing and Certification Institute is combined with digital image processing technology to evaluate the uniformity of the oven's internal temperature field, which is similar to the evaluation of the oven's internal temperature field uniformity in this study [21]. Therefore, DIN 55350-11 proposed by VDE in Germany is selected for a comparative experiment. This section introduces the evaluation method of DIN 55350-11 in detail and compares it with the uniformity evaluation method proposed in this study.

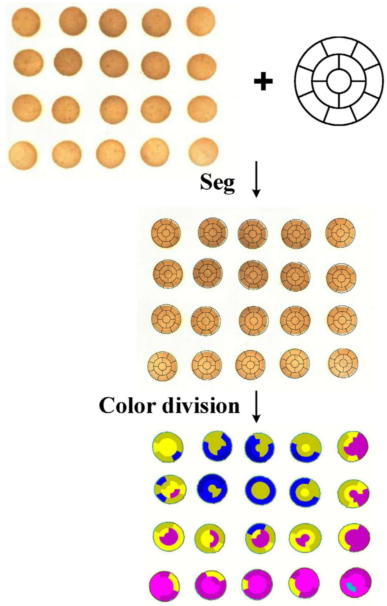


FIGURE 14. Evaluation flow chart of DIN 55350-11.

1) RESULTS OF GERMAN VDE EXPERIMENT

The method DIN 55350-11 selects small round biscuits as baked goods. According to IEC 60350 [22], a single round cookie is divided into thirteen parts. The color of each part of the small round biscuit is compared with the standard color card, and the round cookie image color is divided into seven grades. In this way, DIN 55350-11 qualitatively expresses the color uniformity of the baked goods image based on the standard color card and the size characteristics of the baked goods and thus reflects the uniformity of the temperature field inside the oven. The flowchart of the method is shown in Fig. 14.

2) DISCUSSION OF GERMAN VDE EXPERIMENT RESULTS

The DIN 55350-11 method does not quantitatively express the distribution of the baked state. Moreover, the color division method based on the standard color card comprises certain artificial evaluation errors. Moreover, when dividing baked goods according to IEC 60350 by DIN 55350-11, the size of baked goods needs to be considered by a procedure that may lead to processing errors.

The proposed uniformity evaluation model can solve these problems by qualitatively and quantitatively analyzing the uniformity of the baked state distribution of the baked goods image under the same color characteristic standard. The improved SLIC segmentation algorithm can be used to segment the image, which is not affected by the size of the baked goods. Table 4 is a comparative summary of DIN 55350-11 and the proposed method.

In conclusion, the method proposed in this study is superior with regard to numerous aspects to DIN 55350-11 proposed

TABLE 4. Comparison between DIN 55350-11 and proposed evaluation method.

	DIN 55350-11	OURS
Seg Method	IEC 60350	Improved SLIC
Standard of Division	Standard color card	Color feature: L
Evaluation	Qualitative	Quantitative & Qualitative

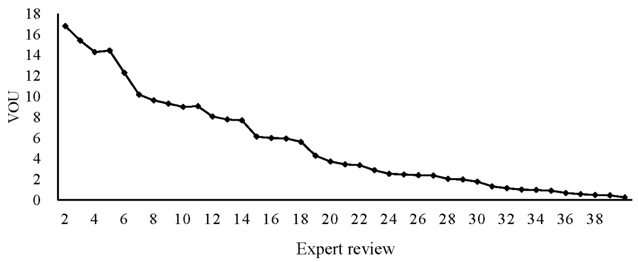


FIGURE 15. Expert review and *VoU* value curve.

by Germany VED. In the process of image segmentation and color division of baked goods, the method proposed in this study realizes complete automation, does not rely on manual operation, and avoids the introduction of manual operation errors. At the same time, the segmentation and color division of baked goods images were based on the characteristics of the baked goods images themselves, and the experimental results were consistent with observation by human eye. Moreover, the method proposed in this study has realized the quantitative expression of the image uniformity of baked goods, which provides a digital basis for the evaluation of uniformity of the temperature field inside the oven.

B. MULTIPLE GROUPS OF COMPARATIVE EXPERIMENTS

In this study, experiments were carried out repeatedly to verify the rationality of the proposed method. In this section, ovens of different brands were used to bake the same formula and same sized toasts, and forty baked goods images were collected with the same camera under the same light and focal length. The uniformity evaluation value of the baked food image was calculated, and the experimental results were displayed and discussed.

1) RESULTS OF MULTIPLE GROUPS OF COMPARATIVE EXPERIMENTS

The baked goods images were processed according to the processes described in Section III. The value of uniformity (VoU) of each baked goods image was obtained. At the same time, the baked goods images were reviewed by experts, and a reliable uniformity ranking was obtained (the sequence number increased from poor to good). Fig. 15 shows the curve of the expert evaluation value and VoU.

Fig. 16 displays the process chart of calculating VoU of some baked goods images in this comparative experiment. The original baked goods images were preprocessed,

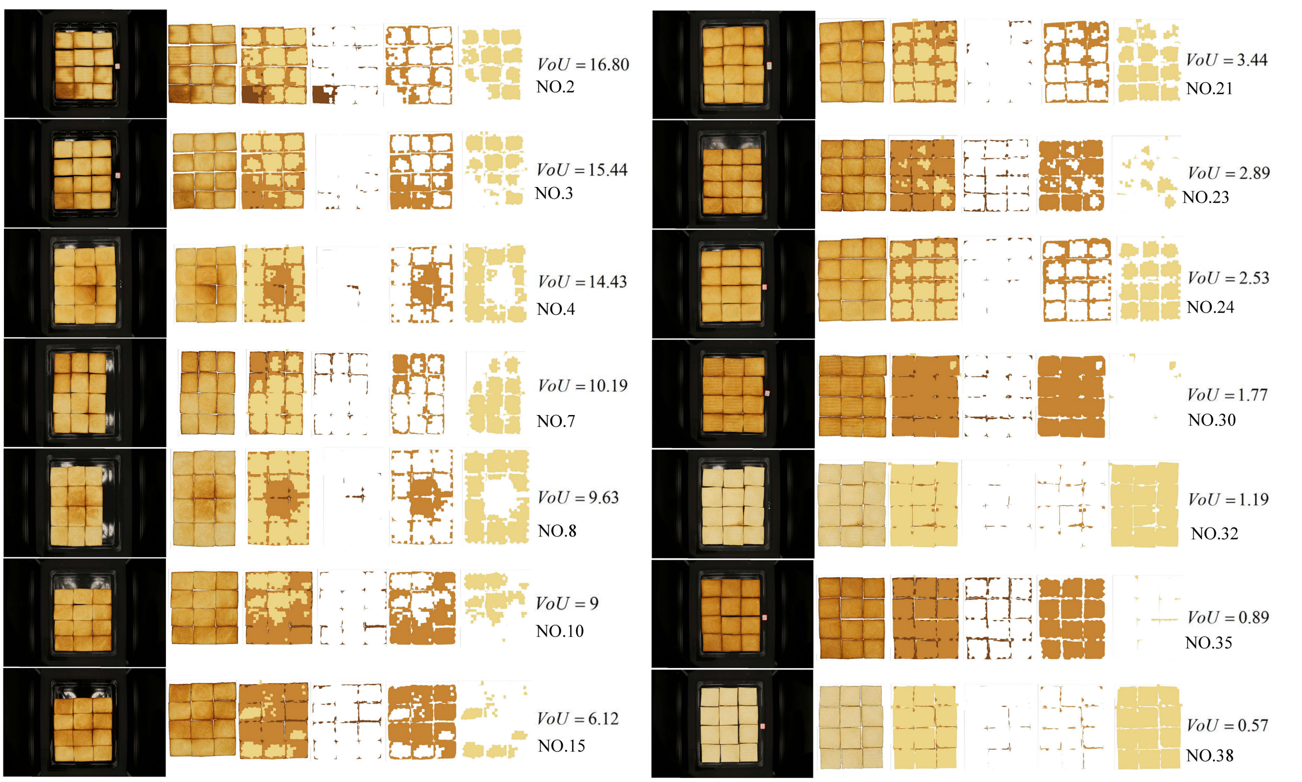


FIGURE 16. Uniformity evaluation process of multi-group baked goods images. From left to right is the raw image of the original baked goods; pre-processed baked goods; baking states map; burn state map; moderately cooked state map; uncooked state map; as well as *VoU* value and expert review serial number.

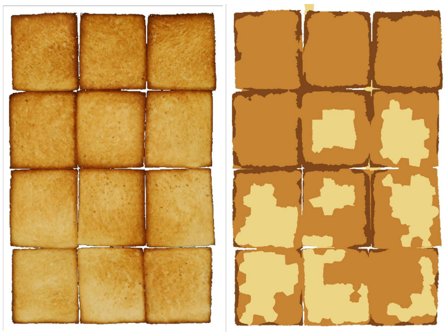


FIGURE 17. Baked goods image of expert review No. 18. (a) demonstrates the baked goods with expert review No. 18 after pretreatment, and (b) is the representation diagram of baked state.

segmented by improved SLIC segmentation, and meshed. Finally, *VoU* was calculated. Fig. 16 illustrates shows the raw baked goods image with NO.X experts review, the pre-processed image of baked goods only, the baked goods states map, the burnt states map, the moderately cooked states map, the uncooked states map, the *VoU* value, and the expert review value NO.X.

2) DISCUSSION ON RESULTS OF MULTIPLE GROUPS OF COMPARATIVE EXPERIMENTS

The curve in Fig. 15 demonstrates that *VoU* is negatively related to the ranking of the expert review; i.e., *VoU* of the baked goods image with poor uniformity identified by the expert evaluation is larger, which is in line with the expected rule. Taking the baked goods image with the expert review serial number 18 as an example, Fig. 17 depicts the baked goods image and the baked states chart of expert review NO.18.

Fig. 17(a) demonstrates the baked goods with expert review No. 18 after pretreatment, and Fig. 17(b) illustrates the representation diagram of baked state. The lower left corner and the middle right corner of Fig. 17(a) are light, the upper and upper left corners of the image are dark, and the edge of each toast block is the darkest area. In Fig. 17(b), the lower left corner and the middle right side depict the uncooked state aggregation areas, and the color of the upper side and the left side of the upper side are the moderately cooked state aggregation areas, which reflects the same rule as that in Fig. 17(a). Therefore, the method proposed in this study does not change the characteristics of the original baked goods image, and enhances the expression of the baked states of the original baked goods image. In addition, the baked states map conforms to the human eye observation.

Table 5 lists the distribution variances and proportions of different baked states, as well as the *VoU* value. The following conclusions can be drawn from Table 5.

1) The proportion of the moderately cooked state is the largest, and the proportion of the burnt state is the smallest.
2) The distribution variance of the uncooked state is the largest; i.e., the distribution of the uncooked state is the most uneven one. The distribution variance of the burnt state is the largest; i.e., the distribution of the burnt state is the most uniform one. Based on the color feature of the baked goods image and the L component value, different baked states were classified according to Table 1. Therefore, it is necessary to analyze the L component value of the baked goods image.

TABLE 5. Evaluation value of uniformity of baked goods image with expert review No. 18.

Baking state	Distribution variances	Proportion(%)	VoU
Burnt	$\sigma_B^2 = 0.25$	$P_B = 6.82$	5.62
Moderate	$\sigma_M^2 = 5.64$	$P_M = 64.56$	
Uncooked	$\sigma_U^2 = 6.85$	$P_U = 28.61$	

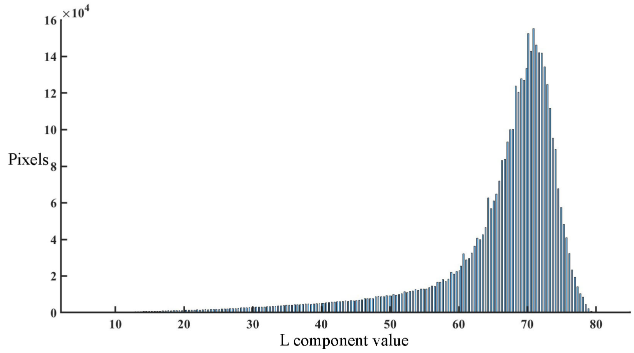


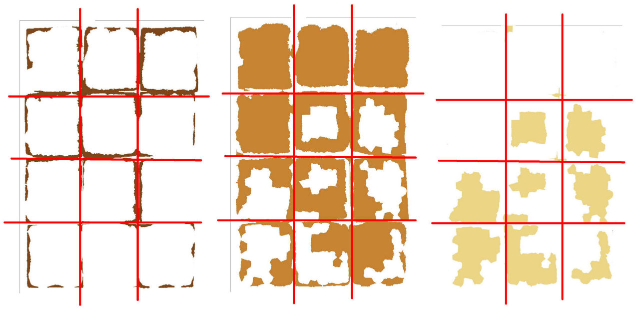
FIGURE 18. *L* Component histogram of baked goods image with expert review No. 18. Fig. 18 maps the distribution of the *L* component value.

According to the state segmentation method in Table 1, the following conclusion can be drawn: the number of pixels in the range of $L \leq 45$ is the smallest; the number of pixels in the range of $45 < L \leq 70$ is the largest; the number of pixels in the range of $70 < L$ is greater. In summary, we draw the following conclusions:

1) The proportion of the baking goods images with the expert review No. 18 in the moderate baked state is the largest, and the proportion of the burnt state is the smallest.
2) The threshold value of the L component value of the baked goods image with No. 18 is wide; thus, the contrast of the image brightness is obvious.

In conclusion, the L component histogram shown in Fig. 18 is consistent with the baked states proportion calculated in Table 5.

In Fig. 19(a), the burnt state is distributed in each grid block; thus, the burnt state has good uniformity. In Fig. 19(b), the moderately cooked state distribution difference of each grid is large. The grids in the upper right and upper left corners almost fill the entire grid, while the grids in the middle of the lower left and right corners do not. Therefore, the moderately cooked state has moderate uniformity. In Fig. 19(c), the uncooked state is not distributed in the upper and upper left grids, while the uncooked state in the lower left and middle right grids almost fills the entire grid. Thus, the uncooked state has the worst uniformity. Therefore, the distribution



(a) (b) (c)

FIGURE 19. Meshing map of baking goods image of expert review No. 18. (a), (b), and (c) show mesh division diagrams of the burnt state, the moderately cooked state, and the uncooked state, respectively.

variances of baked states calculated in Table 5 are consistent with Fig. 19.

To summarize, the distribution variances and proportions of different baked states listed in Table 5 are reliable, and VoU calculated using Eq. 3 is accurate.

Fig. 15 shows that a larger number of expert reviews leads to a smaller the value of VoU. Moreover, by observing the image of baked goods corresponding to the expert review serial number and the VoU value, it can be concluded that the distribution of the image of baked goods with a low VoU value is more uniform than that of the image of baked goods with a high VoU value. The calculation results of the VoU value are consistent with the observation results by human eyes, and they are negatively correlated with the expert review number. The VoU value can explain the uniformity of the baked goods image. Therefore, the uniformity of baked goods images can be reliably evaluated by calculating the VoU of the image.

V. CONCLUSION

In this study, a camera was used to obtain a baked goods image, and a bilateral filter was used to denoise the image. The region of interest was selected, and the background of the selected area was removed to obtain a pure baked goods image. The improved SLIC segmentation was used to extract the baking status. The uniformity of baked goods images was calculated based on the proposed uniformity calculation model. Several comparative experiments were conducted to verify the model results. The experimental results show that the improved SLIC segmentation algorithm can represent the baking status of the baked goods image in the form of a superpixel. VoU can quantitatively express the uniformity of baking status distribution in baked goods images. The proposed method provides a basis for the analysis of the uniformity of the temperature field inside an oven. This method has been applied to the evaluation system of the oven internal temperature field of an enterprise in China, which provides a strong basis for further evaluation of the oven internal temperature field and a new design idea for improving the oven quality. The method proposed in this study is based on the color features of the baked goods image. When classifying the states of baked goods, the color features of the baked goods image are taken as the benchmark, and different classification of the baked food state will affect the uniformity of the baked goods image in calculating the VoU value. In the future, the influence of the baked state classification on the image uniformity of baked goods will be further studied to make the calculation of the VoU value more consistent with the observations by the human eye.

REFERENCES

[1] S. P. Cauvain, *Bread Making: Improving Quality*. New York, NY, USA: CRC Press, 2003.

[2] N. Therdthai and W. Zhou, "Recent advances in the studies of bread baking process and their impacts on the bread baking technology," *Food Sci. Technol. Res.*, vol. 9, no. 3, pp. 219–226, 2003.

[3] N. Chhanwal and A. Tank, "Computational fluid dynamics (CFD) modeling for bread baking process—A review," *Food Bioprocess Technol.*, vol. 5, no. 4, pp. 1157–1172, 2012.

[4] P. Verboven, N. Scheerlinck, J. D. Baerdemaeker, and B. M. Nicolaï, "Computational fluid dynamics modelling and validation of the isothermal airflow in a forced convection oven," *J. Food Eng.*, vol. 43, no. 1, pp. 41–53, Jan. 2000.

[5] J. Smolka, A. J. Nowak, and D. Rybarz, "Improved 3-D temperature uniformity in a laboratory drying oven based on experimentally validated CFD computations," *J. Food Eng.*, vol. 97, no. 3, pp. 373–383, Apr. 2010.

[6] N. Chhanwal, A. Anishaparvin, D. Indrani, K. Raghavarao, and C. Anandharamakrishnan, "Computational fluid dynamics (CFD) modeling of an electrical heating oven for bread-baking process," *J. Food Eng.*, vol. 100, no. 3, pp. 452–460, Oct. 2010.

[7] F. Zhaoqi, Z. Hongnan, W. Rongwu, and Q. Xiaohong, "Uniformity detection of nonwovens based on digital image processing," *Ind. Textiles*, vol. 35, no. 1, pp. 36–43, 2017.

[8] H. Zhifu, Z. Yi, L. Naixing, and L. Rui, "Real time monitoring and evaluation method of asphalt mixture paving uniformity based on digital image processing technology," *Highway Transp. Technol.*, vol. 34, no. 4, pp. 8–15 and 79, 2017.

[9] Z. Fei, L. Yuan, L. Deqiang, and Z. Dabo, "Method for evaluating casing uniformity of tobacco strips based on image processing," *Tobacco Sci. Technol.*, vol. 48, no. 11, pp. 65–68, 2015.

[10] F. Yan, H. Mingyi, Y. Huajing, and W. Jiang, "A glass uniformity inspection system based on image processing," *Comput. Appl.*, vol. 4, pp. 64–66, Apr. 2004.

[11] S. Lakshmi and D. Sankaranarayanan, "A study of edge detection techniques for segmentation computing approaches," *Int. J. Comput. Appl.*, vol. 1, pp. 35–41, Aug. 2010.

[12] K. M. Pooja and R. Rajesh, "Image segmentation: A survey," in *Proc. Int. Conf. Recent Adv. Math.*, Aug. 2016, pp. 521–527.

[13] T. Zuva and O. O. Olugbara, "Image segmentation, available techniques, developments and open issues," *Can. J. Image Process. Comput. Vis.*, vol. 2, no. 3, pp. 20–29, 2011.

[14] K. Fukunaga and L. Hostetler, "The estimation of the gradient of a density function, with applications in pattern recognition," *IEEE Trans. Inf. Theory*, vol. IT-21, no. 1, pp. 32–40, Jan. 1975.

[15] Y. Cheng, "Mean shift, mode seeking, and clustering," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 17, no. 8, pp. 790–799, Aug. 1995.

[16] R. Achanta, A. Shaji, K. Smith, A. Lucchi, P. Fua, and S. Süsstrunk, "SLIC superpixels compared to state-of-the-art superpixel methods," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 34, no. 11, pp. 2274–2282, Nov. 2012.

[17] A. Schick, M. Fischer, and R. Stiefelhagen, "Measuring and evaluating the compactness of superpixels," in *Proc. 21st Int. Conf. Pattern Recognit. (ICPR)*, Nov. 2012, pp. 930–934.

[18] Z. Fang, W. Zhang, and H. Ma, "Breast cancer classification with ultrasound images based on SLIC," in *Proc. 9th Int. Conf. Frontier Comput. (FC)*, 2019.

[19] R. Sethi and S. Indu, "Local enhancement of SLIC segmented underwater images using gray world based algorithm," in *Proc. 9th Int. Conf. Adv. Pattern Recognit. (ICAPR)*, Dec. 2017, pp. 1–6.

[20] M. D. Bah, A. Hafiane, and R. Canals, "Weeds detection in UAV imagery using SLIC and the Hough transform," in *Proc. 7th Int. Conf. Image Process. Theory, Tools Appl. (IPTA)*, Nov. 2017, pp. 1–6.

[21] *Quality Management Concepts*, document DIN 55350-11, 2008.

[22] *Household Electric Cooking Appliances*, document IEC 60350, 2016.

[23] E. Masad and J. W. Button, "Unified imaging approach for measuring aggregate angularity and texture," *Comput.-Aided Civil Infrastruct. Eng.*, vol. 15, no. 4, pp. 273–280, Jul. 2000.

[24] P. Karthikeyan and S. Vasuki, "Multiresolution joint bilateral filtering with modified adaptive shrinkage for image denoising," *Multimed Tools Appl.*, vol. 75, no. 23, pp. 16135–16152, Dec. 2016.

[25] S. A. Shanthi, C. H. Sulochana, and S. A. Jerome, "Image denoising using bilateral filter in subsampled pyramid and nonsubsampled directional filter bank domain," *J. Intell. Fuzzy Syst.*, vol. 31, no. 1, pp. 237–247, Jun. 2016.

[26] I. Pitas, "Digital image processing algorithms and applications," *IEEE Signal Process. Mag.*, vol. 18, no. 2, p. 58, 2002.

[27] M. S. Millán and E. Valencia, "Color image sharpening inspired by human vision models," *Appl. Opt.*, vol. 45, no. 29, p. 7684, Oct. 2006.

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