Robust photometric invariance in machine color vision
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Chapter 7

Summary and Discussion

Summary

The goal of the thesis is (1) to obtain photometric invariant image processing methods, and (2) to obtain these results robustly. The multispectral image processing methods described in the thesis are derived from the physics-based dichromatic reflection model. This makes it possible to characterize what kinds of images are likely to be segmented successfully by our algorithm. The model describes the reflection of materials which are optically inhomogeneous. Many common materials have these characteristics, including most paints, varnishes, paper, ceramics, and plastics, etc. Therefore, we anticipate that images of objects of these materials are properly processed by the proposed methods described in the thesis.

A uniformly colored object satisfying the dichromatic reflection model may give rise to a broad spectrum of color values due to the dependence of the measured color on the geometry of the object and due to specularities. For many industrial machine vision tasks, it is required to visually inspect objects independent of these photometric effects. To that end, the color data should be transformed into color invariant spaces. However, it was shown in the thesis that, given certain input RGB-values or spectra, the output values for invariant color models may become unstable under the presence of sensor noise. A possible way to deal with unstable color values is to generate the reliability of a transformed color together with the output and to incorporate the reliability in the image processing methods. Summarizing, the aims of the thesis are:

1. To derive an expression of uncertainty associated with the output of an image processing method.
2. To exploit the obtained expression to improve automatic visual inspection methods.
3. To visually inspect objects using multispectral images made invariant to some or more of the photometric effects described above.
The results obtained in the thesis are discussed per chapter in the following paragraphs.

Chapter 2: Color Measurement by Imaging Spectrometry In the chapter, the effect of photon noise is propagated to estimate the uncertainty in reflection percentages, and in $XYZ$ and CIE $L^*a^*b^*$ values. Comparison between the actual and estimated uncertainties shows that the model for noise propagation gives reasonable predictions of the actual uncertainties. Therefore, in chapter 2 a positive result is obtained for the first aim. The expression of uncertainty is then used to obtain an estimate that a measured color is within one CIE $L^*a^*b^*$ unit of the actual color. The result is important for an automated color inspection system: The predicted uncertainty is available for the decision of what action needs to be taken if a measured color difference exceeds a predefined threshold. Therefore, in chapter 2 a positive result is obtained for the second aim. The reflection percentages measured by the spectrograph are compared to that of a spectrophotometer. The measurements were made under different light sources. Still, the difference in measured reflectance percentages showed to be on average only 2%. The measurements were therefore shown to be invariant to the spectral power distribution (SPD) of the illumination due to the calibration procedure described in the chapter. Therefore, a positive result is also obtained for the third aim of the thesis.

Chapter 3: Density Estimation for Color Images In the chapter, a novel method for density estimation for normalized color images and hue images is presented. Models are derived that propagate the sensor uncertainty to the uncertainty in the normalized and hue color values. Experiments show that the predicted uncertainties compare favorably to the actual uncertainties. Therefore, a positive result is obtained for the first aim of the thesis. Next, a principled way for variable kernel density estimation is proposed that incorporates the estimated reliability of the transformed color values. It is verified empirically that the proposed method is less sensitive to sensor noise and unstable color values. This way, a positive result is obtained for the second aim of the thesis.

Chapter 4: Parameter-Free Thresholding and Classification of Color Edges To visually inspect objects, the object contours may be of interest. In chapter 4, the uncertainty associated with the gradient strength in $RGB$, normalized, and hue color space is estimated. Hereby, the first aim of the thesis is achieved. The uncertainty is employed to distinguish edges resulting from sensor noise from real edges caused by photometric effects or material transitions. The reliability of method is verified empirically in the chapter, achieving the second aim. Employing the dichromatic reflection model, it is derived that the different color spaces are invariant to different photometric effects. The knowledge is used to classify object contours in the following types: (1) a shadow or geometry edge, (2) a highlight edge, and (3) a material edge. The proposed method is verified empirically for objects known to satisfy the dichromatic reflection model. This way, a positive result is obtained for
the third aim of the thesis.

Chapter 5: Robust Photometric Invariant Segmentation of Multispectral Images  In the chapter, different distance measures are compared. The goal is to find measures which can be used for photometric invariant image segmentation. Using the dichromatic reflection model, it is concluded that polar angular representations allow for photometric invariant detection of both matte and shiny surfaces. The result therefore meets the third aim of the thesis. However, it is also shown that the representation may become unstable in the presence of sensor noise, a problem shared by other photometric invariant color spaces, see the previous chapters. It is investigated whether an estimate can be obtained for the propagation of uncertainty due to sensor noise to the uncertainty in polar angles. The estimates are compared to the actual uncertainties and a very reasonable correspondence between the uncertainties is observed. Hereby, the first aim of the thesis is achieved. Finally, the estimated uncertainty is employed in the region detection method to be robust against sensor noise, meeting the second aim of the thesis.

Chapter 6: Recovering the Spectral Power Distribution of the Illumination in Multispectral Images  The chapter employs successfully the segmentation method developed in the previous chapter. The goal is to obtain the SPD of the light source. The result can be used to separate the SPD of the illumination from the surface albedo. This way, objects can be inspected independent of the SPD of the illumination, thereby achieving the third aim of the thesis.

Discussion

In the discussion, the results from various chapters are compared. The first aim of the thesis is to derive an expression of uncertainty associated with the output of an image processing method. To that end, equation (2.9) introduces a camera model describing the relation between the number of photons counted at a pixel and the resulting output gray level at that pixel. Equation (2.10) describes sensor noise as a Poisson distribution. Combining the camera and noise model, the uncertainty associated with a gray value is obtained. The uncertainty is then propagated through image processing routines using Eqs. (2.7) and (2.8). These equations are then used throughout the remainder of the thesis.

Consider the term color image processing function. With the term, the transformation is meant from a spectrum measured at a single pixel to, e.g., its corresponding hue value. In chapter 2, the uncertainties in the sensor values are propagated to the reflectance percentages and to the uncertainties in XYZ and CIE L*a*b* values. In chapter 3, this is repeated for normalized RGB and hue color values, in chapter 4 for opponent colors, and in chapter 5 for the two polar angle representations of spectra. The reliability of the obtained estimates of uncertainty is tested empirically in chapters 2 through 5. Both RGB images as well as multispectral images are used
in the experiments. The chapters show a striking correspondence between the estimated and actual uncertainties. The correspondence is even more impressive taking the simplicity of the camera, noise and error propagation models into account.

In contrast to color image processing functions, in chapter 4 the error propagation formulae of (2.7) and (2.8) are interpreted as a spatial image processing functions. With the term, image processing function are meant which operate on pixel values at neighboring locations. Doing so, the uncertainty in the gradient strength is estimated. The uncertainty is successfully applied in parameter-free edge thresholding. From these results, it is concluded that indeed it is possible to derive an expression of uncertainty associated with both color and spatial image processing functions, using a single framework.

The second aim of the thesis is to exploit the obtained expression associated with the output of an image processing method to improve visual inspection methods. Chapter 2 discusses color measurement in an industrial inspection context. Here, a measured color is compared to a reference color, and these colors should be the same unless an error occurred in the production process. The obtained expression of uncertainty is used to answer the question what the probability is that the measured color falls within one CIE $L^*a^*b^*$ unit of the reference color. In chapter 3, the expression of uncertainty is used for the parameterization of variable kernel density estimation. In chapter 4, the expression is applied successfully to derive an edge detector which automatically and locally discards false edges. In chapters 5 and 6, the estimated uncertainty was employed in the region detection method to be robust against sensor noise. From these results, it is concluded that indeed it is possible to exploit the expression of uncertainty to improve visual inspection.

The third aim of the thesis is to visually inspect objects using multispectral images made invariant to photometric effects. In the second chapter, color measurements made with two different instruments are shown to be invariant to the SPD of the illumination. The result was obtained taking prior knowledge of the SPD of the illumination into account. However, such prior knowledge may not always be available. Therefore, the goal of chapter 6 of the thesis is to obtain the SPD of the light source automatically. This way, independence of the actual SPD of the illumination can be achieved.

Employing the dichromatic reflection model, in chapter 4 it is derived that the normalized color space is photometric invariant for the geometry of matte objects. Also, it is derived that the opponent color space is photometric invariant for highlights for shiny surfaces. The knowledge is used to classify object contours in the following types: (1) a shadow or geometry edge, (2) a highlight edge, and (3) a material edge.

In chapter 5, the dichromatic reflection model is used to establish that the hue polar angle representation of spectra is invariant to both the geometry of objects and for highlights. The chromaticity angle representation is invariant only to the geometry of objects. The results allow to segment images invariant to orientation of the camera, light source and surface normal thereby meeting the third aim of the thesis.

On the basis of the theoretical and experimental results, it is concluded that understanding the error propagation of sensor noise through image processing methods can be exploited successfully to obtain robust photometric invariance.