



Eötvös Loránd University
Faculty of Informatics
Department of Numerical Analysis

Color image analysis and recognition using quaternion Zernike moments

TDK thesis

Supervisor:
Zsolt Németh
Assistant Professor

Author:
Gergely Nagy
Computer Science MSc
1st year

Budapest, 2020

Abstract

Image moments and moment invariant features are widely used for image analysis and pattern recognition. The system of orthogonal Zernike polynomials (defined over the complex unit disk) proved to be a useful basis for series expansions because of certain invariance properties.

Conventionally, for multichannel color images, RGB decomposition or grayscale conversion was used. However, in the recent past, quaternion algebra has been employed to various conventional moments to analyze a color image holistically. Guo and Zhu [1] introduced quaternion Fourier-Mellin moments (QFMMs) which are an extension of the conventional Fourier-Mellin moments for the grayscale image. They also proposed their invariants on rotation, scale, and translation for color object recognition. Chen et al. [2] proposed the quaternion Zernike moments (QZMs), generally overperforming other similar approaches in these aspects, due to the natural invariances of Zernike functions. The same quaternion techniques were applied successfully to other function systems (e.g. [3, 4]), yielding similar results.

In this thesis we introduce a method of transforming a digital RGB image inside the unit circle onto a points system providing discrete orthogonality. Using this points system for the discretization of the QZMIs, we have achieved significant improvements in the image recognition and reconstruction capabilities of the method, especially under noisy conditions.

Contents

1	Introduction	3
1.1	Contributions	4
1.2	Structure of the paper	4
2	Background	6
2.1	Image moments	6
2.2	Zernike moments	7
2.3	Quaternions and color image moments	8
2.4	Discretization of QZMs	11
2.5	Quaternion Zernike Moment Invariants (QZMIs)	14
2.6	Applications	15
3	Proposed method for discretization	17
4	Implementation	20
4.1	Programming language and libraries used	20
4.2	Calculating moments and moment invariants	20

4.3	New image transformation	24
5	Tests and comparison with the original method	30
5.1	Test images	30
5.2	Invariance test	34
5.3	Image reconstruction	37
5.4	Image recognition	41
5.5	Template matching	48
6	Conclusion	50
6.1	Future possibilities	51
Bibliography		52

Chapter 1

Introduction

Moment invariants are widely used in applications for pattern matching [5], image recognition [6], or to extract useful features from images [7].

Most of the moments are defined for single-channel, grayscale images, however extending these techniques to multichannel color images is an important and generally unresolved problem with many possible applications. Conventionally, for color images either RGB decomposition or grayscale conversion was used in order to utilize the methods defined for grayscale images. This may lead to loss of information, for example in the case of grayscale conversion (where the average of the color channels is taken) some color information can be lost.

More recently, the algebra of quaternions has been used to extend the single-channel methods to color images. For example, quaternion Fourier-Mellin moments have been introduced as an extension of the conventional Fourier-Mellin moments [1], as well as the quaternion Zernike moments as an extension of the conventional Zernike moments [8].

The Zernike functions are a system of orthogonal functions defined over the unit disk. Using these functions as a basis for series expansions proved to be useful because of certain inherent invariance properties. Zernike moments, and by extension quaternion Zernike moments are defined by these functions.

Considering a digital image as a discrete sampling of an image function defined over a continuous domain, the need arises to discretize the computation of these moments. One important property of the discretization of these methods defined by orthogonal functions is to preserve the orthogonality over the discrete system, so as to avoid redundancy and achieve high robustness with respect to noise.

The conventional method for discretizing quaternion Zernike moments (used by Chen et al. [2]) consists of uniformly distributed points over the unit disk. This method does not achieve discrete orthogonality thus decreasing the robustness of the moments.

Our goal was to create a system over which the quaternion extension of the Zernike functions is discrete orthogonal and thus improve the robustness of quaternion Zernike moments and to decrease the error introduced by discretization.

1.1 Contributions

In this thesis a new method is proposed for the discretization of quaternion Zernike moments over the unit disk. A points system is constructed on the unit disk, over which the Zernike functions extended to quaternions are discrete orthogonal.

This new method is compared to the method used by Chen et al. [2]. For the tests, image sets from the Columbia Object Image Library [9] and the Amsterdam Library of Object Images [10] were used.

Besides the theoretical invariance properties of QZMIs, these are also verified empirically. The image reconstruction capabilities of both methods are compared and we find that the proposed method decreases the error of reconstruction significantly.

The methods are also applied to the recognition of rotated, scaled and translated (RST transformed) images with varying levels of either Gaussian or salt-and-pepper noise. We find that with respect to Gaussian noise the new method achieves significantly better rates of recognition, even for images with high noise values. For salt-and-pepper noise no significant difference can be found between the capabilities of the methods. Additionally, we also show that by decreasing the number of points used for discretization, the new method is able to achieve similar results as the original method with high number of points, but the computational need to obtain these results is much lower using the new method.

1.2 Structure of the paper

This section serves as an overview of the structure of this thesis and contains a short summary of each chapter.

Chapter 1 serves as an introduction, where the motivation for this work is described and the contributions featured in this paper are presented.

Chapter 2 provides the background for our work. The core concepts, such as (quaternion) Zernike moments and invariants are described in detail. A summary of previous methods for the discretization of quaternion Zernike moments is also given. Finally, some applications relying on Zernike moments are described.

The method we propose for the discretization of Zernike moments is presented in Chapter 3. The construction of a discrete orthogonal points system and the proof of discrete orthogonality is also given.

The different methods and technologies used for the computation of the invariants is shown in Chapter 4. The computation of the proposed new system is also described.

Chapter 5 contains the description of all the tests conducted on the methods, such as image reconstruction or recognition. The results of these tests are evaluated and the original and proposed methods are compared.

Finally, Chapter 6 summarizes the work and results presented in this thesis. Future development possibilities are also presented.

Chapter 2

Background

This chapter contains a short summary of the concepts used in this thesis, and previous results this work is based upon, such as image moments, their relevance in image analysis, and more specifically Zernike moments and their state-of-the-art applications for both grayscale and color image analysis. Furthermore, some of the the most common use cases of image moments are provided.

2.1 Image moments

In general, image moments are certain descriptive values calculated using the pixel intensities of an image. Different moments can be used to extract certain properties from a picture, for example the centroid of a grayscale image can be calculated as

$$\{\bar{x}, \bar{y}\} = \left\{ \frac{M_{10}}{M_{00}}, \frac{M_{01}}{M_{00}} \right\},$$

where M_{ij} are the regular (geometric) image moments defined as

$$M_{ij} = \sum_x \sum_y x^i y^j I(x, y), \quad (2.1)$$

with $I(x, y)$ being the pixel value at the coordinates (x, y) .

Moment invariants

Using specific image moments, so-called moment invariants can be defined, which are invariant under certain transformations, such as rotation, scaling, and translation.

These invariants are widely used in applications for pattern matching and image recognition [5, 11, 12]. In particular, moment invariants can be used in medical applications, such as solving the Pathological Brain Detection problem [13].

2.2 Zernike moments

Zernike functions, first introduced by Zernike [14] in 1934 are a system of complex, orthogonal polynomials defined on the unit disc. Using polar coordinates the Zernike polynomials $V_{n,m}$ ($n \in \mathbb{N}$, $m \in \mathbb{Z}$, $n \geq |m|$ and $n - |m|$ is even) are defined as

$$V_{n,m}(r, \theta) = R_{n,m}(r)e^{im\theta},$$

where $R_{n,m}(r)$ are the radial polynomials defined as

$$R_{n,m}(r) = \sum_{k=0}^{\frac{n-|m|}{2}} \frac{(-1)^k (n-k)!}{k! \left(\frac{n+|m|}{2} - k\right)! \left(\frac{n-|m|}{2} - k\right)!} r^{n-2k}. \quad (2.2)$$

It is important to note that these radial polynomials are the same for m and $-m$, and satisfy an orthogonality relation over $[0, 1]$ with respect to the weight r (see e.g. [15]), i.e. for a fixed m we have

$$\int_0^1 R_{n,|m|}(r) R_{n',|m|}(r) r dr = \frac{1}{2n+2} \delta_{n,n'}, \quad (2.3)$$

and can be expressed in terms of the shifted Jacobi polynomials in the following way:

$$R_{n,m}(r) = r^{|m|} P_{\frac{n-|m|}{2}}^{(0,|m|)}(2r^2 - 1), \quad (2.4)$$

where we denoted the k -th degree classical Jacobi polynomials by $P_k^{(\alpha,\beta)}$ (see e.g. [16]).

Zernike moments are image moments, defined for grayscale images inside the unit circle, using the Zernike polynomials. The system of Zernike polynomials proved to be a suitable basis for series expansions in numerous optical applications (see for example [17–19]), and moment invariants could easily be constructed using the Zernike moments [20].

The Zernike moment of order n and repetition m of a grayscale, continuous image function $f(r, \theta)$ given in polar coordinates is defined as

$$Z_{n,m}(f) = \frac{n+1}{\pi} \int_0^1 \int_0^{2\pi} f(r, \theta) V_{n,m}^*(r, \theta) r dr d\theta.$$

Since the Zernike polynomials are orthogonal, the following approximate reconstruction of the image function is possible, using Zernike moments only up to a finite M degree:

$$f(r, \theta) \approx \sum_{n=0}^M \sum_{m=-n}^n Z_{n,m}(f) V_{n,m}(r, \theta).$$

Since digital images are not represented in polar coordinates and are not defined only over the unit disc, a transformation of the image onto the unit disk is needed. The most commonly used transformation is a linear transformation from the image coordinates to a suitable square inside the unit circle. This transformation is described in more detail in Section 2.4. After the linear transformation, the following discrete approximation can be used to calculate the Zernike moments of a digital image $f(x, y)$

$$Z_{n,m}(f) = \frac{2(n+1)}{\pi(N-1)^2} \sum_{x=1}^N \sum_{y=1}^N f(x, y) V_{n,m}^*(r_{x,y}, \theta_{x,y}),$$

where N is the size of the image, and $(r_{x,y}, \theta_{x,y})$ are the polar coordinates corresponding to the (x, y) image coordinates.

2.3 Quaternions and color image moments

The previously defined Zernike moments can only be used for grayscale images, and extending signal processing techniques efficiently to multichannel color images is an important and generally unresolved problem.

Conventionally, for multichannel, color images, two main approaches are being used. Either the image is converted to grayscale so that the moments defined for grayscale images could be used, or (after RGB-decomposition) the grayscale method is used on each channel of the image [21].

More recently, the algebra of quaternions was employed to various conventional moments so that color images can be analysed holistically.

Quaternion representation of color images

A quaternion, q , was defined by Hamilton [22] as a generalization of the complex numbers:

$$q = a + bi + cj + dk.$$

The real numbers a, b, c and d are called the components of q , and the imaginary units $\mathbf{i}, \mathbf{j}, \mathbf{k}$ are defined according to the following rules:

$$\begin{aligned}\mathbf{i}^2 &= \mathbf{j}^2 = \mathbf{k}^2 = \mathbf{ijk} = -1, \\ \mathbf{ij} &= -\mathbf{ji} = \mathbf{k}, \quad \mathbf{jk} = -\mathbf{kj} = \mathbf{i}, \quad \mathbf{ki} = -\mathbf{ik} = \mathbf{j}.\end{aligned}$$

Therefore, the set of quaternions \mathbb{H} is an *algebra*, where a quaternion is called pure quaternion when $a = 0$. The conjugate and modulus of q are respectively defined by

$$\begin{aligned}q^* &= a - b\mathbf{i} - c\mathbf{j} - d\mathbf{k}, \\ |q| &= \sqrt{a^2 + b^2 + c^2 + d^2}.\end{aligned}$$

Ell and Sangwine [23] utilized quaternions to represent a color image, $f : \mathbb{R}^2 \rightarrow \mathbb{R}^3$, as follows:

$$f(x, y) = \mathbf{i}f_R(x, y) + \mathbf{j}f_G(x, y) + \mathbf{k}f_B(x, y),$$

where functions $f_R, f_G, f_B : \mathbb{R}^2 \rightarrow \mathbb{R}$ represent the red, green and blue components of the (x, y) pixel, respectively.

For example, Guo and Zhu [1] introduced quaternion Fourier-Mellin moments (QFMMs) which are an extension of the conventional Fourier-Mellin moments. Similarly, the same quaternion techniques were applied successfully to other function systems (e.g. [3, 4]), yielding similar results.

Quaternion Zernike moments

Chen et al. [2, 8] proposed the quaternion Zernike moments (QZMs), an extension of conventional Zernike moments to color images using quaternions. Generally, this method overperforms other similar approaches in color image recognition, due to the natural invariances of Zernike functions.

Quaternion Zernike moments, just as regular Zernike moments, are defined over the complex unit disk

$$\mathbb{D} = \left\{ z = re^{i\theta} \in \mathbb{C} : r \in [0, 1], \theta \in [0, 2\pi) \right\}.$$

The main difference, compared to the conventional Zernike moments is that instead of the complex-valued Zernike functions, QZMs use a quaternion-valued generalization of the Zernike functions as a basis for the series expansion. The quaternion generalizations of classical Zernike functions, defined as

$$\phi_{n,m}(r, \theta) = R_{n,m}(r)e^{-\mu m\theta},$$

satisfy the orthogonality relation

$$\frac{n+1}{\pi} \int_0^1 \int_0^{2\pi} \phi_{n,m}(r, \theta) \phi_{n',m'}^*(r, \theta) r d\theta dr = \delta_{n,n'} \delta_{m,m'}. \quad (2.5)$$

Let $f(r, \theta)$ be a pure quaternion valued, RGB image function with a continuous domain, defined in polar coordinates on the unit circle \mathbb{D} . Each color component corresponds to one of the imaginary units. Let $\mu = \frac{i+j+k}{\sqrt{3}}$ be a unit pure quaternion.

Since the multiplication of quaternions is not commutative, both right-side and left-side quaternion Zernike moments can be defined. The right-side QZM of order n and repetition m is defined as

$$Z_{n,m}^R(f) = \frac{n+1}{\pi} \int_0^1 \int_0^{2\pi} R_{n,m}(r) f(r, \theta) e^{-\mu m \theta} r dr d\theta, \quad (2.6)$$

$n \geq |m|$ and $n - |m|$ is even.

The left-side QZMs are defined as

$$Z_{n,m}^L(f) = \frac{n+1}{\pi} \int_0^1 \int_0^{2\pi} R_{n,m}(r) e^{-\mu m \theta} f(r, \theta) r dr d\theta.$$

Similarly to non-quaternion Zernike moments, the original image can be approximated by using either right-side or left-side QZMs only up to a finite M degree.

$$\begin{aligned} f(r, \theta) &\approx \sum_{n=0}^M \sum_{m=-n}^n Z_{n,m}^R(f) R_{n,m}(r) e^{\mu m \theta} \\ f(r, \theta) &\approx \sum_{n=0}^M \sum_{m=-n}^n e^{\mu m \theta} Z_{n,m}^L(f) R_{n,m}(r) \end{aligned} \quad (2.7)$$

In this thesis, only the right-side QZMs will be used, because of the following relation between right- and left-side QZMs:

$$Z_{n,m}^L(f) = -(Z_{n,m}^R(f))^*$$

The discretization of the QZMs and the transformation of arbitrary digital RGB images onto the unit disk is described in detail in Section 2.4

2.4 Discretization of QZMs

The conventional Zernike moments and the QZMs are defined in terms of polar coordinates, for image functions, whose domain is the unit disk. On the other hand, digital images are usually defined in image coordinates, with the coordinates being integers ranging from 0 to $N - 1$ (the number of pixels along each axis).

There are two "natural" ways to linearly transform a square image from image coordinates to polar coordinates inside the unit circle, using only translation and scaling [24].

The first method is to transform the entire image inside the unit circle, as shown on Figure 2.1. This way all of the pixels will be used for calculating the (quaternion) Zernike moments, but some areas of the unit disk will remain empty, no pixels fall on those areas.

The other method is to transform the image such that the unit disk becomes the inscribed circle of the square image, as shown on Figure 2.2. This method fills the entire unit disk with pixels, but some pixels fall outside the unit circle and thus will not be used for the calculation of (quaternion) Zernike moments.

The polar coordinates (r, θ) corresponding to the image coordinates (x, y) can be calculated by the following formulas, which is the mapping proposed by Chong et al. [25]:

$$r = \sqrt{(c_1 x + c_2)^2 + (c_1 y + c_2)^2},$$

$$\theta = \tan^{-1} \left(\frac{c_1 y + c_2}{c_1 x + c_2} \right),$$

where $c_1, c_2 \in \mathbb{R}$ depend on which of the previously mentioned transformations is used. A $\lambda \in \mathbb{R}$ scaling factor is also defined for each transformation. For the first one (Figure 2.1): $c_1 = \frac{\sqrt{2}}{N-1}$, $c_2 = -\frac{1}{\sqrt{2}}$, and $\lambda = \frac{2}{\pi}$. While for the other transformation (Figure 2.2): $c_1 = \frac{2}{N-1}$, $c_2 = -1$ and $\lambda = 1$.

In general, using the polar form of the transformed coordinates, the continuous integral of (2.6) can be replaced by discrete approximations of form

$$Z_{n,m}^R(f) \approx \lambda_{n,m} \sum_{k=1}^{N_1} \sum_{j=1}^{N_2} f(r_k, \theta_j) \phi(r_k, \theta_j) w(r_k, \theta_j), \quad (2.8)$$

with some discretization weight function w and normalization constants $\lambda_{n,m}$.

Using either one of the previously defined transformations, a points system on the unit disk is obtained, and for each point exactly one pixel value is assigned. When this

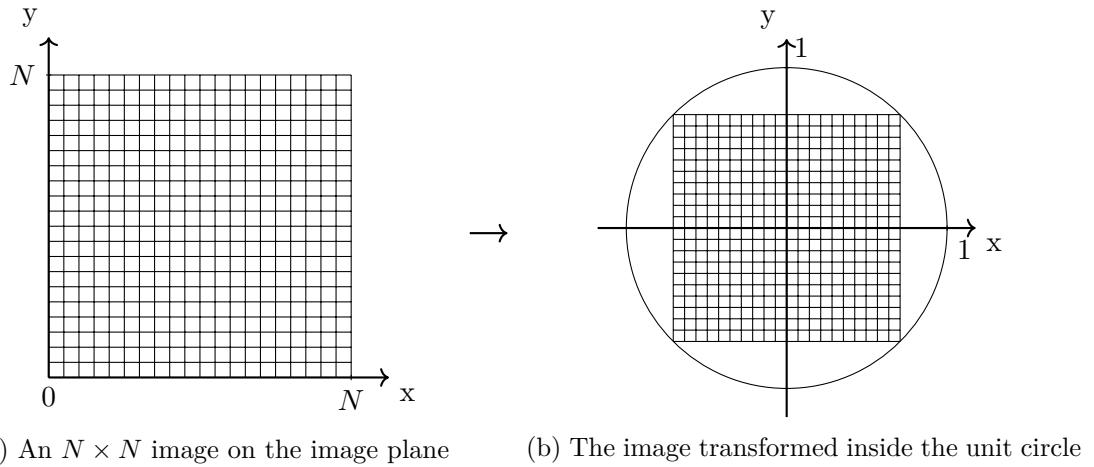


Figure 2.1: The image before and after applying the transformation inside the unit disk

points system is used for the discretization of QZMs, the following formula can be used to approximate the QZMs of the original image function:

$$Z_{n,m}^R(f) \approx \lambda \frac{n+1}{(N-1)^2} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} R_{n,m}(r_{x,y}, \theta_{x,y}) f(x, y) e^{-\mu m \theta_{x,y}},$$

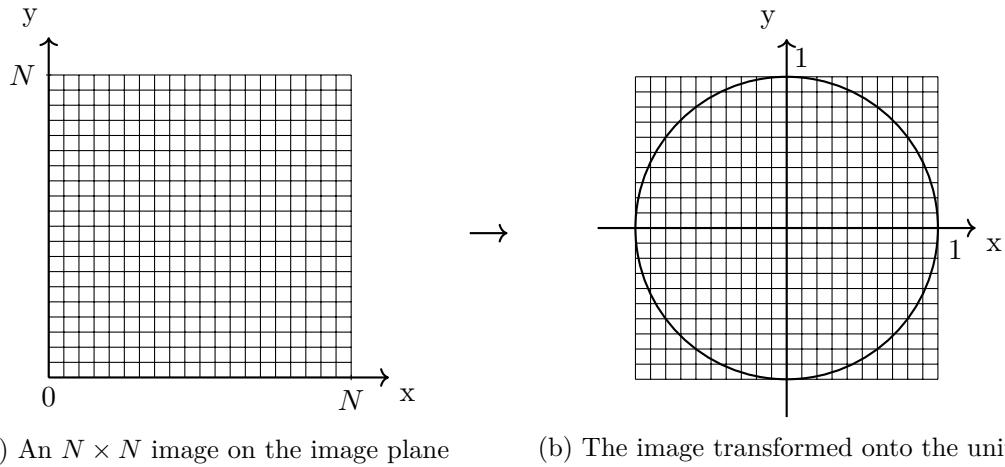
where $f \in \mathbb{R}^2 \rightarrow \mathbb{H}$ is the RGB image defined in image coordinates, $(r_{x,y}, \theta_{x,y})$ are the polar coordinates belonging to the image coordinates (x, y) , and λ is the previously defined scaling factor.

In the rest of this thesis, for comparison purposes, the transformation of the image inside the unit circle will be used as Chen et al. [2] used this discretization to present their results.

Other approaches for discretization

A similar approach was utilized numerous times in the literature, substituting the radial polynomial system $R_{n,m}$ of Zernike functions with other well-known orthogonal systems over the radial interval $[0, 1]$. For color image analysis, further examples of this include the QFMMs [1], the QPETs, QPCTs and QPSTS [26], the QCMS [27], the QBFMs [28], the QRHFMs [29], the QG-CHFMs and QG-PJFMs [30] and the QSBFMs [31].

This natural method was proven susceptible to inaccuracies of both geometric and numeric nature when applied to grayscale images (see e.g. [32], [33]), and these problems are carried over to the quaternion generalizations as well. Later in [34], a more accurate



(a) An $N \times N$ image on the image plane (b) The image transformed onto the unit disk

Figure 2.2: The image before and after applying the transformation onto the unit disk

computational technique was proposed, where \mathbb{D} is partitioned into polar sectors of approximately equal areas, and the original pixels are transformed to the centroids of these via cubic interpolation, and the weights are computed by performing the integration of functions $\phi_{n,m}$ over the respective polar sectors.

The same idea, adapted to quaternion-type moments for any aforementioned radial system, could substantially improve performances for tasks like image reconstruction, as well as recognition after rotation, scaling and translation (RST) transformations and addition of different kinds of noise; and the reason for this is essentially the improved accuracy gained for the computation of respective moments and invariants. Examples of this technique applied for color images include the papers of Hosny and Darwish for Legendre [35] and Chebyshev [36] radial systems.

A drawback of this approach is that the cubic interpolation applied for coordinate transformation is irreversible, so another transformation with further introduced error is required if one wishes to reconstruct the original square/rectangle shaped image. Instead, in the previous works [32–36], reconstruction error was measured for the transformed image and its reconstructions on disc \mathbb{D} only. Another, although minor issue is the natural smoothing provided by the cubic interpolation, which unintentionally improves the obtained results for experiments on noisy images by filtering some of the noise, a sometimes unwanted side effect for one who wants to compare the performances of the moments themselves. To ensure fair comparisons with the first transformation group, linear interpolation should be used, ensuring invertible coordinate transformations, and also excluding unwanted side effects.

Finally, the results of Wang et al. [37] and Liu et al. [38] for radial harmonic Fourier moments are some of the recent advances in the study of quaternion moments, introduc-

ing a novel coordinate transformation, which seems to improve accuracy for this specific function system while maintaining fast computation times, without utilizing cubic interpolation at all. These improvements may seem surprising at first, but hopefully our results will clarify the theoretical reason behind them.

Discrete orthogonality

Even though the Zernike polynomials are a set of orthogonal polynomials on the complex unit disk, the previously defined points systems do not provide discrete orthogonality. This is problematic, and results in poor performances especially for applications under noisy conditions. Also, the lack of orthogonality makes the moment representation of an image redundant, hence introducing unwanted reconstruction errors.

2.5 Quaternion Zernike Moment Invariants (QZMIs)

Chen et al. [2, 8] proposed the constructions described in this section in order to create rotation, scaling and translation invariant moment invariants using the quaternion Zernike moments.

Translation invariance

In order to achieve translation invariance, the common centroid of all three color channels can be calculated by using zero-order and first-order geometric moments, as described by Suk and Flusser [21]. If the origin of the polar coordinate system is placed on this common centroid (x_c, y_c) , then the QZMs calculated in this coordinate system will be translation invariant. Let $\overline{Z}_{n,m}^R(f)$ denote the translation invariant QZMs.

Rotation invariance

To achieve rotation invariance consider the image rotated by some degree α : $f'(r, \theta) = f(r, \theta - \alpha)$. Chen et al. [2] proved that for the rotated image $Z_{n,m}^R(f') = Z_{n,m}^R(f)e^{-\mu m \theta}$ and $Z_{n,m}^L(f') = e^{-\mu m \theta} Z_{n,m}^L(f)$. Because of the these properties

$$\Phi_{n,k}^m = Z_{n,m}^R(f) Z_{k,-m}^L(f) = -Z_{n,m}^R(f) (Z_{k,m}^R(f))^*$$

is invariant to rotation. In the following chapters, this will be referred to as a quaternion Zernike moment rotation invariant (QZMRI).

Previously, the modulus $|Z_{n,m}^R(f)|$ was used to achieve rotation invariance [8], but this provided only one real-valued invariant, whereas the following construction provides a quaternion-values invariant.

Scaling invariance

For non-negative integers m and l , Chen et al. [2] constructed the following scaling invariants utilizing the symmetric property of the radial polynomials with respect to m and an alternate form of the QZMs.

$$c_{m,l}^{t,k} = (-1)^{l-k} \frac{(m+2l+1)(m+k+l)!}{(l-k)!(k-t)!(m+k+t+1)!}$$

$$L_{m+2l,m}^R(f) = \sum_{t=0}^l \sum_{k=t}^l \left(\sqrt{|Z_{0,0}^R(f)|} \right)^{-(m+2k+2)} c_{m,l}^{t,k} Z_{m+2t,m}^R(f).$$

Combined RST invariance

Similarly to using QZMs to define rotation invariants, the previously defined scaling invariants can also be used to construct $\Psi_{n,k}^m = L_{n,m}^R(f)(L_{k,m}^R(f))^*$, which is invariant to rotation and scaling.

In order to achieve translation invariance, throughout the construction of the scaling invariants $L_{n,m}^R$ the translation invariant QZMs ($\bar{Z}_{n,m}^R(f)$) can be used, thus defining the $\bar{L}_{n,m}^R$ translation and scaling invariants.

Furthermore, $\bar{\Psi}_{n,k}^m = \bar{L}_{n,m}^R(f)(\bar{L}_{k,m}^R(f))^*$ is invariant to rotation, scaling and translation [2]. This is called a quaternion Zernike moment invariant (QZMI).

2.6 Applications

Zernike moments and moment invariants are a useful tool in optical and medical applications. Specifically, Zernike moments can be used in the representation of optical aberration [17–19].

Furthermore, applications in pattern recognition have shown that in noisy environments

Zernike moment yield the best results [6]. Castro-Ortega et al. [39] have used Zernike moment invariants to extract descriptions of hand vein patterns.

Another application is in image watermarking so that the watermark is invariant to transformations and robust against noise [40–42].

Finally, one possible application is to use Zernike moments in conjunction with neural networks. The robustness of neural networks with respect to noise is a known shortcoming of current systems [43, 44]. Zernike moments can be used to extract features of images with high robustness to noise, so these extracted features can be used as input for neural networks [7, 45].

Chapter 3

Proposed method for discretization

In this chapter we describe our proposed approach to the discretization of continuous quaternion Zernike moments. Our aim is to ensure simple and reversible computability, but achieve considerable reduction in potential computational inaccuracies at the same time. For this, we define a system of sampling points (r_k, θ_j) , over which the integral discretization (2.8) maintains advantageous theoretical properties. The idea behind our approach is motivated by the work [15].

Fix a positive integer N . Let us denote by $\rho_{k,N}$, $k = 1, \dots, N$ the roots of the N -th order Legendre polynomial [16]. Notating the fundamental polynomials of Lagrange interpolation with respect to the roots $\rho_{k,N}$ as $\ell_{k,N}$, we define the constants

$$\mathcal{A}_{k,N} = \int_{-1}^1 \ell_{k,N}(x) dx, \quad (k = 1, \dots, N).$$

Then, the system of sampling points X_N over the unit disk \mathbb{D} is defined in polar form by

$$X_N \ni (r_{k,N}, \theta_{j,N}) = \left(\sqrt{\frac{1 + \rho_{k,N}}{2}}, \frac{2\pi j}{4N} \right), \quad (k = 1, \dots, N, j = 1, \dots, 4N),$$

and the respective weight values and constants are

$$w(r_{k,N}, \theta_{j,N}) = \frac{\mathcal{A}_{k,N}}{8N}, \quad \lambda_{n,m} = n + 1, \quad (3.1)$$

so the generated integral approximation based on (2.8) is

$$\frac{1}{\pi} \int_0^1 \int_0^{2\pi} f(r, \theta) d\theta dr \approx \int_{X_N} f = \sum_{k=1}^N \sum_{j=1}^{4N} f(r_{k,N}, \theta_{j,N}) \frac{\mathcal{A}_{k,N}}{8N}.$$

We remark that the values $\mathcal{A}_{k,N}$ are somewhat close to $\frac{1}{N}$, so the weighting is close to being uniform.

What is appealing in this choice of X_N is the fact that the orthogonality of quaternion Zernike functions (2.5) is preserved under changing to discrete integration over this set of points, i.e.

Theorem 1. *Suppose that for $n, n' \in \mathbb{N}$ naturals and $m, m' \in \mathbb{Z}$ integers we have*

$$\frac{n+n'}{2} + \min(|m|, |m'|) < 2N.$$

Then

$$(n+1) \int_{X_N} \phi_{n,m} \phi_{n',m'}^* = \delta_{n,n'} \delta_{m,m'}.$$

Proof. Let us consider the radial orthogonality relation (2.3) expressed with the Jacobi polynomials of (2.4), i.e.

$$\begin{aligned} \frac{1}{2n+2} \delta_{n,n'} &= \int_0^1 R_{n,|m|}(r) R_{n',|m|}(r) r dr = \\ &\int_0^1 r^{2|m|} P_{\frac{n-|m|}{2}}^{(0,|m|)}(2r^2 - 1) P_{\frac{n'-|m|}{2}}^{(0,|m|)}(2r^2 - 1) r dr, \end{aligned}$$

and apply a change of variable $u = 2r^2 - 1$, to obtain

$$\frac{1}{2n+2} \delta_{n,n'} = \frac{1}{4} \int_{-1}^1 \left(\frac{1+u}{2}\right)^{2|m|} P_{\frac{n-|m|}{2}}^{(0,|m|)}(u) P_{\frac{n'-|m|}{2}}^{(0,|m|)}(u) du.$$

Notice that here the integrand is a polynomial of degree $\frac{n+n'}{2} + |m| < 2N$, so the exact value of the integral is equal to the value of the Gauss-Legendre quadrature (see e.g. [16]), i.e.

$$\frac{1}{2n+2} \delta_{n,n'} = \frac{1}{4} \sum_{k=1}^N \mathcal{A}_{k,N} \left(\frac{1+\rho_{k,N}}{2}\right)^{2|m|} P_{\frac{n-|m|}{2}}^{(0,|m|)}(\rho_{k,N}) P_{\frac{n'-|m|}{2}}^{(0,|m|)}(\rho_{k,N}).$$

Rewriting this in terms of $r_{k,N} = \sqrt{\frac{1+\rho_{k,N}}{2}}$ gives a discrete orthogonality relation for the radial polynomials, as

$$\frac{1}{2n+2} \delta_{n,n'} = \frac{1}{4} \sum_{k=1}^N \mathcal{A}_{k,N} R_{n,m}(r_{k,N}) R_{n',m}(r_{k,N}). \quad (3.2)$$

Now we can proceed with proving the statement.

$$\int_{X_N} \phi_{n,m} \phi_{n',m'}^* = \sum_{k=1}^N \sum_{j=1}^{4N} \phi_{n,m}(r_{k,N}, \theta_{j,N}) \phi_{n',m'}^*(r_{k,N}, \theta_{j,N}) \frac{\mathcal{A}_{k,N}}{8N} = \\ \frac{1}{8N} \left(\sum_{j=1}^{4N} e^{-\mu m \theta_{j,N}} e^{\mu m' \theta_{j,N}} \right) \left(\sum_{k=1}^N \mathcal{A}_{k,N} R_{n,m}(r_{k,N}) R_{n',m'}(r_{k,N}) \right),$$

and since quaternions $-\mu m \theta_{j,N}$ and $\mu m' \theta_{j,N}$ commute, we have

$$\sum_{j=1}^{4N} e^{-\mu(m-m')\frac{2\pi j}{4N}} = 4N \delta_{m,m'}$$

for the first sum, so if $m \neq m'$, the discrete integral equals to 0 and we are done.

Suppose $m = m'$, now we are left with

$$\int_{X_N} \phi_{n,m} \phi_{n',m}^* = \frac{1}{2} \sum_{k=1}^N \mathcal{A}_{k,N} R_{n,m}(r_{k,N}) R_{n',m}(r_{k,N}) = \frac{1}{n+1} \delta_{n,n'},$$

where we used (3.2) for the last equation as we have $\frac{n+n'}{2} + |m| < 2N$. \square

Theoretically, the discrete orthogonality relation of Theorem 1 means that the exact values of right and left moments can be computed, provided we can measure the function values over X_N , for a sufficiently large N : let us consider an arbitrary linear combination of right moments (2.6) in the form

$$f \approx f_N(r, \theta) = \sum_{n+m<2N} \sum Z_{n,m}^R(f) \phi_{n,m}^*(r, \theta),$$

then the exact value of the moment $Z_{n,m}^R(f)$, using the previous result, is

$$Z_{n,m}^R(f) = \int_{X_N} f_N \phi_{n,m},$$

and the same can be said for the left moments. This proves that for system X_N , the discretization error is zero, a property that no other previously used quaternion moment method possessed. Besides this, only numerical roundoffs and the moment order threshold $f \approx f_N$ generates computational inaccuracies.

Chapter 4

Implementation

This chapter presents the tools and methods used for implementing a program for calculating the QZMIs of an image using both methods of discretization.

4.1 Programming language and libraries used

The implementation was created using the Python programming language [46] and relying on the Numpy [47] and Numba [48] libraries to achieve efficient and fast computation of the moment invariants, as well as the Python Imaging Library (PIL, Pillow) [49] for image manipulation.

Numpy provided a way to efficiently work with arrays and matrices. It also provided the quaternion package, which supports the quaternion data type.

Using the just-in-time compilation (JIT) capabilities of Numba (i.e. the `@jit` annotation), the computationally heavy parts of the implementation could be made almost as fast as native code. The disadvantage of using JIT is that it limits the available types and functions, so in the implementation the use of `@jit` is kept only to the critical, computationally intensive functions.

4.2 Calculating moments and moment invariants

To obtain the quaternion Zernike moment invariants (QZMIs) of an image as described in Section 2.5, the quaternion Zernike moments (QZMs) must be calculated first. Chen

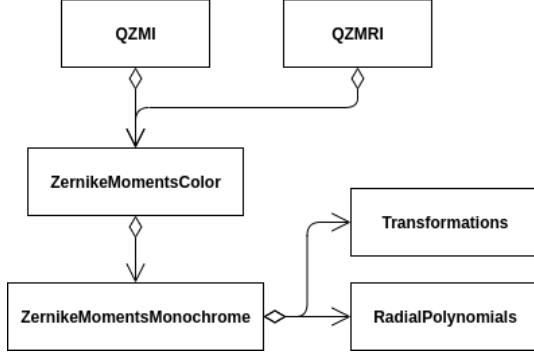


Figure 4.1: The relationships between the classes used to calculate QZMIs and QZMRIs

et al. [2] showed that instead of calculating the QZMs directly by using the algebra of quaternions, it is possible to calculate the real and the imaginary parts of the quaternion-valued QZM individually by using some linear combination of the real and imaginary parts of the complex-valued, single channel Zernike moments. This means that the single channel Zernike moments have to be calculated for all three of the RGB color channels. Furthermore, the calculation of the Zernike moments requires the computation of the radial polynomials, introduced in (2.2).

To calculate the required values, the following four classes were created, each relying on the next one to perform the computation.

- **QZMI**, for calculating the quaternion Zernike moment invariants
- **ZernikeMomentsColor**, for calculating the quaternion-valued Zernike moments
- **ZernikeMomentsMonochrome**, for calculating the complex-valued, single channel Zernike moments
- **RadialPolynomials**, for calculating the values of the radial polynomials at a given point

The relationships between these classes are shown on Figure 4.1, as well as the **QZMRI** class, which calculates the rotation invariant QZMs needed for some test cases. A description of the algorithms used in these classes and the data stored by them is given below.

Since the work presented in this thesis involves changing the way an image is transformed from image coordinates to polar coordinates inside the unit circle, the classes were made modular with respect to the transformation used. This makes it easy to create and

```

1 @jit(void(float64, int32, float64[:, :], nopython=True)
2 def calculateRadialPolynomials(r, P, values):
3     values[0,0] = 1
4     values[1,1] = r
5     for n in range(2,P + 1):
6         h = n*(n - 1)*(n - 2)
7         K2 = 2*h
8         values[n,n] = (r**n)
9         values[n,n-2] = n*values[n,n] - (n-1)*values[n-2,n-2]
10        for m in range(n-4,-1,-2):
11            K1 = (n + m)*(n - m)*(n - 2)/2
12            K3 = (-1)*m*m*(n - 1) - h
13            K4 = (-1)*n*(n + m - 2)*(n - m - 2)/2
14            r2 = r**2
15            values[n,m] = ((K2*r2+K3)*values[n-2,m]+K4*values[n-4,m])/K1

```

Figure 4.2: Function for calculating radial polynomial values

test a new image transformation function with the interface expected by the calculating classes.

Radial polynomials

To calculate the value of all $R_{n,m}$ radial polynomials up to some maximal degree P at a point $r \in [0, 1]$, the modified Kintner's method was used, as described in [24]. This algorithm computes the value of $R_{n,m}(r)$ for all $0 \leq |m| \leq n \leq P$, ($n - |m|$ is even) with complexity $\mathcal{O}(N^2)$. This method is ideal for the computation of all radial polynomial values up to a maximum degree.

Since this method is called many times during the calculation of Zernike moments, just-in-time compilation was used to further increase efficiency. Figure 4.2 shows the JIT-enabled function.

Complex Zernike moments

The `ZernikeMomentsMonochrome` class calculates the conventional Zernike moments of degree at most P of a square $N \times N$, single channel (grayscale) image. The algorithm is based directly on the discretized definition of the Zernike moments. For the original

linear transformation of the image onto the unit disk, this gives:

$$\begin{aligned}
Z_{n,m}(f) &= \lambda \frac{(n+1)}{(N-1)^2} \sum_{x=1}^N \sum_{y=1}^N f(x,y) V_{n,m}^*(r_{x,y}, \theta_{x,y}) \\
&= \lambda \frac{(n+1)}{(N-1)^2} \sum_{x=1}^N \sum_{y=1}^N f(x,y) R_{n,m}(r_{x,y}) e^{-im\theta_{x,y}} \\
&= \lambda \frac{(n+1)}{(N-1)^2} \sum_{x=1}^N \sum_{y=1}^N f(x,y) R_{n,m}(r_{x,y}) (\cos(m\theta_{x,y}) - i \sin(m\theta_{x,y})),
\end{aligned}$$

where $0 \leq |m| \leq n \leq P$, $n-|m|$ is even, $(r_{x,y}, \theta_{x,y})$ are the (x, y) coordinates transformed to the unit disk, λ is the scaling parameter also given by the transformation (as described in Section 2.4) and f is the real-valued, grayscale image.

By precomputing the sin and cos values for all possible m and $\theta_{x,y}$ values, as well as the values of the radial polynomials, this formula gives an efficient way of calculating the real and imaginary parts of the Zernike moments separately. This way only primitive data types have to be used during the computation and it can be made more efficient using JIT.

Also, there is no need to calculate the Zernike moments for negative m values, as the $Z_{n,m}(f) = Z_{n,-m}(f)^*$ identity can be used later to obtain those values.

Quaternion Zernike moments

The class `ZernikeMomentsColor` calculates the quaternion Zernike moments of an RGB image. First, the conventional Zernike moments for each of the three color channels are calculated, then the relationship between QZMs and Zernike moments is used to construct the quaternions [2].

$$\begin{aligned}
Z_{n,m}^R(f) &= -\frac{1}{\sqrt{3}} (\text{Im}(Z_{n,m}(f_R)) + \text{Im}(Z_{n,m}(f_G)) + \text{Im}(Z_{n,m}(f_B))) \\
&\quad + \left[\text{Re}(Z_{n,m}(f_R)) + \frac{1}{\sqrt{3}} (\text{Im}(Z_{n,m}(f_G)) - \text{Im}(Z_{n,m}(f_B))) \right] \mathbf{i} \\
&\quad + \left[\text{Re}(Z_{n,m}(f_G)) + \frac{1}{\sqrt{3}} (\text{Im}(Z_{n,m}(f_B)) - \text{Im}(Z_{n,m}(f_R))) \right] \mathbf{j} \\
&\quad + \left[\text{Re}(Z_{n,m}(f_B)) + \frac{1}{\sqrt{3}} (\text{Im}(Z_{n,m}(f_R)) - \text{Im}(Z_{n,m}(f_G))) \right] \mathbf{k},
\end{aligned}$$

where f is an RGB image and f_R, f_G, f_B are the red, green and blue color channels respectively.

Again, only the QZMs $Z_{n,m}^R$ ($m \geq 0$) are calculated, because for $m < 0$ the $Z_{n,m}^R(f) = Z_{n,-m}^R(f)^*$ equality can be used.

Invariants

The class **QZMI** is responsible for computing the combined rotation, scaling and translation (RST) invariant moments, while the class **QZMRI** computes the moments which are invariant only to rotation. The invariants for scaling and rotation are calculated directly using the QZMs, based on the formulas described in Section 2.5.

To achieve translation invariance, the common centroid of the RGB image is calculated based on the formulas described by Suk and Flusser [21].

$$\{x_c, y_c\} = \left\{ \frac{M_{10}(f_R) + M_{10}(f_G) + M_{10}(f_B)}{M_{00}(f_R) + M_{00}(f_G) + M_{00}(f_B)}, \frac{M_{01}(f_R) + M_{01}(f_G) + M_{01}(f_B)}{M_{00}(f_R) + M_{00}(f_G) + M_{00}(f_B)} \right\},$$

where f_R, f_G, f_B are the grayscale images corresponding to the red, green and blue color channels respectively, and M_{10}, M_{01}, M_{00} are the regular image moments introduced in (2.1). The original image f is then translated in image coordinates such that the origin falls on the common centroid $\{x_c, y_c\}$, and the other invariants are then calculated based on this translated image.

4.3 New image transformation

The new image transformation, as described in Chapter 3, requires the calculation of the roots of the n^{th} degree Legendre polynomials P_n , as well as calculating the integrals of the Lagrange basis polynomials over the roots of P_n . Furthermore, since when applying the linear transformation from image coordinates to polar coordinates, the pixels of the image do not fall exactly on any point in the new discrete points system, other interpolating methods have to be used to approximate the image values at these points.

Because of the modularity of the previously described classes, it is possible to swap the old transformation to the new one. With some minor modifications during the calculation of the conventional Zernike moments because of the new discretization formula containing a different measure, the previous classes can be used to obtain the QZMIs using the new method of discretization.

Roots of Legendre polynomials

The roots of the Legendre polynomial P_n are essential for the calculation of the new points system. An explicit formula, which gives the roots does not exist, thus an efficient and fast iterative algorithm is needed to calculate these roots.

The n^{th} degree Legendre polynomial P_n satisfies the following differential equation:

$$(1 - x^2)P_n''(x) - 2xP_n'(x) + n(n + 1)P_n(x) = 0. \quad (4.1)$$

A fast algorithm for calculating the roots of P_n , based on this differential equation was presented by Glaser et al. [50]. The algorithm uses a second-order Runge-Kutta method (namely the midpoint method) to solve the Prüfer-transformed version of (4.1) for some given initial condition. A first approximation for a root of P_n can be obtained from the solution of the initial value problem. This approximation is then further refined by Newton's method. Subsequent roots can be calculated using the same method but starting from different initial conditions defined by the previous root.

In practice, this algorithm calculates the roots of P_n with accuracy up to machine precision in only a fix, limited number of iterations for both the Runge-Kutta and the Newton's method.

Computing the discrete measure

To calculate the Zernike moments over the discrete orthogonal points system, besides the $\lambda_{n,m} = n + 1$ scaling factor, a weight function is used as well (as described in (2.8)). To calculate these $w(r_{k,N}, \theta_{j,N})$ weight values (defined in (3.1)), the following integral has to be calculated:

$$\mathcal{A}_{k,N} = \int_{-1}^1 \ell_{k,N}(x) dx,$$

where $\ell_{k,N}$ is the k^{th} Lagrange basis polynomial corresponding to the roots of the Legendre polynomial P_N .

The Gauss-Legendre quadrature is based on the roots of the Legendre polynomial P_n of degree n . Let x_1, x_2, \dots, x_n be the roots of P_n .

$$\begin{aligned} \int_{-1}^1 f(x) dx &\approx \sum_{k=1}^n w_k f(x_k), \\ w_k &= \frac{2}{(1 - x_k^2)(P'_n(x_k))^2}. \end{aligned}$$

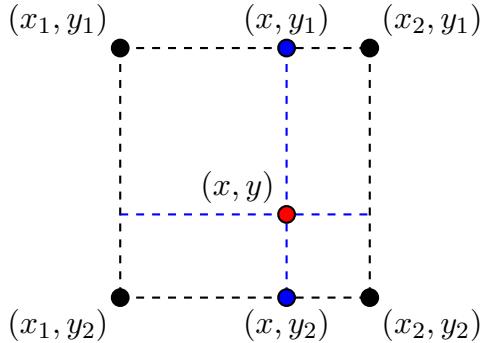


Figure 4.3: The point (x, y) and its neighboring points, which are used to approximate $f(x, y)$ by bilinear interpolation

The quadrature is exact for all polynomials whose degree is at most $2n - 1$. Now $\ell_{k,N}(x)$ is an $N - 1$ degree polynomial, so the Gauss-Legendre quadrature with $n = N$ is exact for $\ell_{k,N}$. Furthermore, $\ell_{k,N}$ is defined such that $\ell_{k,N}(x_i) = 0$ for $i \neq k$, and $\ell_{k,N}(x_k) = 1$. Thus:

$$\int_{-1}^1 \ell_{k,N}(x) dx = w_k = \frac{2}{(1 - x_k^2)(P'_n(x_k))^2}.$$

Since the roots of the Legendre polynomial P_N must be computed to obtain the points system, this formula gives an easy and fast way to calculate the exact values of $\mu_{k,N}$.

Image interpolation

After obtaining the discrete orthogonal points system the values of the image function have to be approximated at each point, because the original pixel values do not fall exactly on the new points. Now we describe some reasonable ways of resampling the image data to fit these new points.

First, the image is linearly transformed onto the unit disk using the transformation shown on Figure 2.2, so that the transformed image covers the entire unit disk. This transformation is used as opposed to the one on Figure 2.1, because the points system covers the entire unit disk, so the image also has to cover the whole disk.

There are two ways to approximate the values at each point, depending on the number of points in the discrete orthogonal points system.

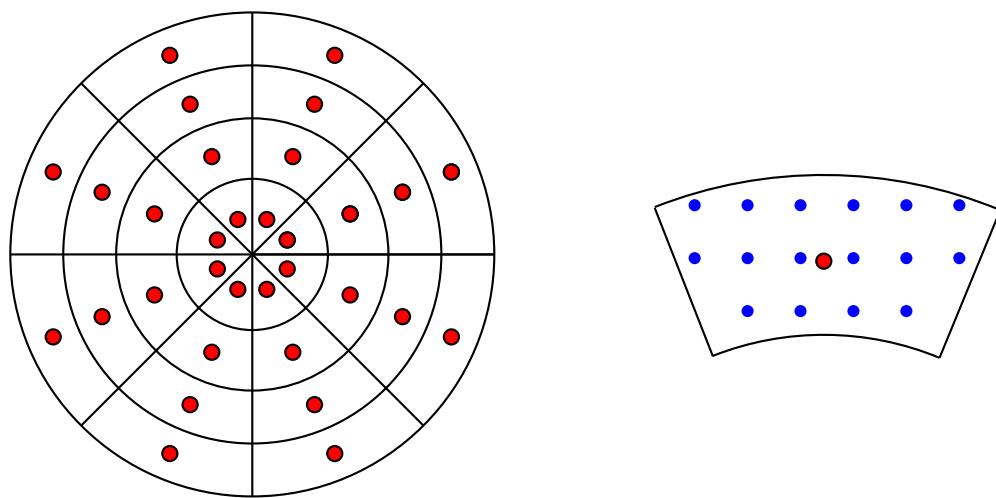
Approximately the same number of points as pixels. If the number of points is approximately the same as the number of pixels in the image, then bilinear interpolation can be used for each point.

First, the four pixels of the image that are closest to the given point (x, y) are determined. These four points form a square. Then, the weighted average of these points is calculated along the x axis, giving approximate function values at two points, which only differ in their y coordinate. Finally, the weighted average of the function values at these points is calculated to get the approximation of $f(x, y)$. The points involved in this interpolation are shown on Figure 4.3.

Much less points than the number of pixels. If the number of points is far less than the number of pixels, then using bilinear interpolation many of the original pixel values would not be represented in the final approximate function values. Therefore, the following algorithm is used to approximate function values using discrete integration.

First, for each pixel in the original image, determine which point it falls closest to after the linear transformation. Then, for each point in the discrete orthogonal points system, calculate the average of the pixels that are closest to that point. This algorithm divides the unit disk into annular sections based on the proximity to the new points. This is shown on Figure 4.4.

The comparison between one of the original transformations and the two methods for approximating function values is shown on Figure 4.5 on the peppers image from the USC-SIPI Image Database [51].



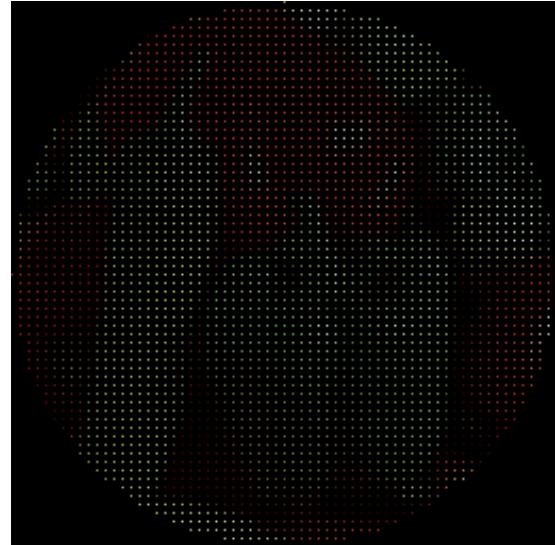
(a) The points system on the unit disk and the annular sectors over which the pixel values are averaged.

(b) A single annular sector with the original image pixels (blue) and the point in which the approximate function value has to be calculated (red).

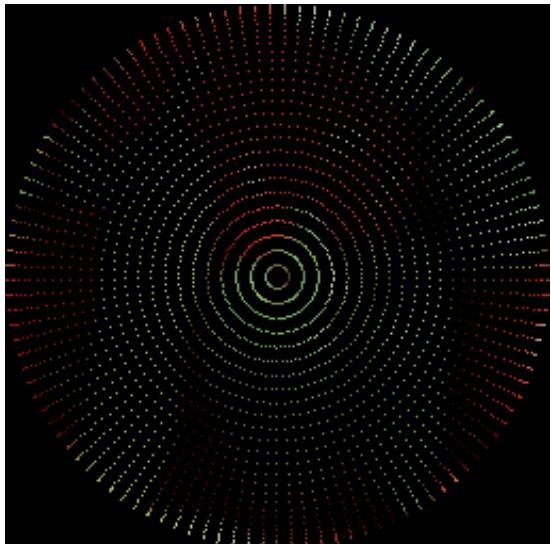
Figure 4.4



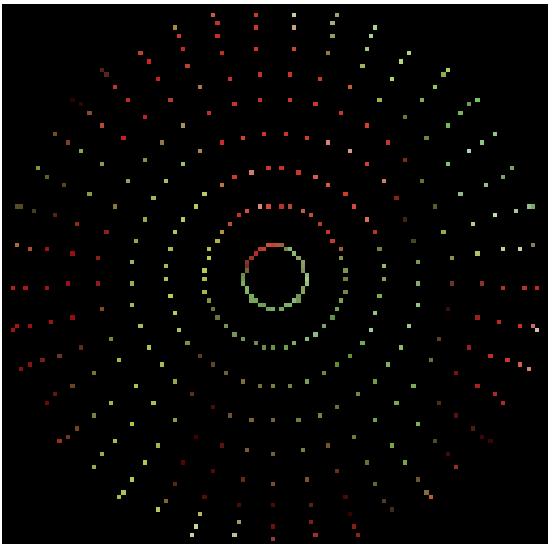
(a) Original image



(b) Original transformation



(c) Bilinear interpolation



(d) Interpolation by integrals

Figure 4.5: Different transformations with different interpolation methods of the peppers image.

Chapter 5

Tests and comparison with the original method

In this chapter we present the different tests that were performed to compare the capabilities of the old and new methods. For each test, the results of both methods of discretization are compared.

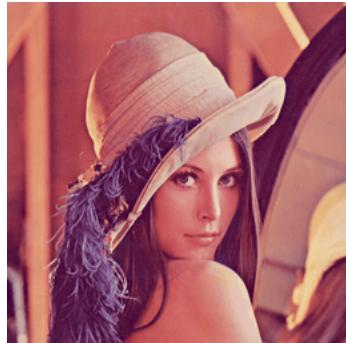
In total, four kinds of tests were conducted:

- Invariance
- Image reconstruction
- Image recognition
- Template matching

5.1 Test images

The images for testing were acquired from multiple online image libraries. The Lenna and Pepper images [51] (shown on Figure 5.1) were used to test image reconstruction as well as to demonstrate the different points systems.

For the image recognition tests, two sets of images were used. The first set consists of 14 images chosen from the Columbia Object Image Library (COIL-100) [9], shown on Figure 5.2. These images are originally 128×128 pixels, but they were placed on a



(a)



(b)

Figure 5.1: The Lenna and Pepper images

204×204 black background so that the rotated, scaled and translated versions of the images stay completely within these dimensions.

A set of 1008 rotated images was created by rotating each of the 14 images by a degree $\alpha \in \{0, 5, 10, \dots, 350, 355\}$. Some examples of the extended and rotated images are shown on Figure 5.3.

Another set of 1176 rotated, scaled and translated images was created by translating each image by -11 pixels in the x direction and 9 pixels in the y direction. Then the translated images were rotated by $\alpha \in \{0, 30, 60, \dots, 300, 330\}$. Finally, each rotated and translated image was scaled by $\lambda \in \{0.5, 0.75, \dots, 1.75, 2\}$. When either scaling or rotation required, bilinear interpolation was used. Some examples of the RST transformed images are shown on Figure 5.4.

Another set of 13 images was acquired from the Amsterdam Library of Object Images (ALOI) [10]. These are shown on Figure 5.5. Originally, these size of these images was 768×576 pixels, but they were downsampled to 96×72 and subsequently extended to 152×128 by placing the images on a black background. Similarly to the test sets created using the COIL-100 images, the ALOI images were also translated, rotated and scaled, yielding a set of 1092 RST transformed images. The parameters of the transformation were the same as for the COIL-100 images, except for the translation, where $\Delta x = 8$ and $\Delta y = 5$ was used.

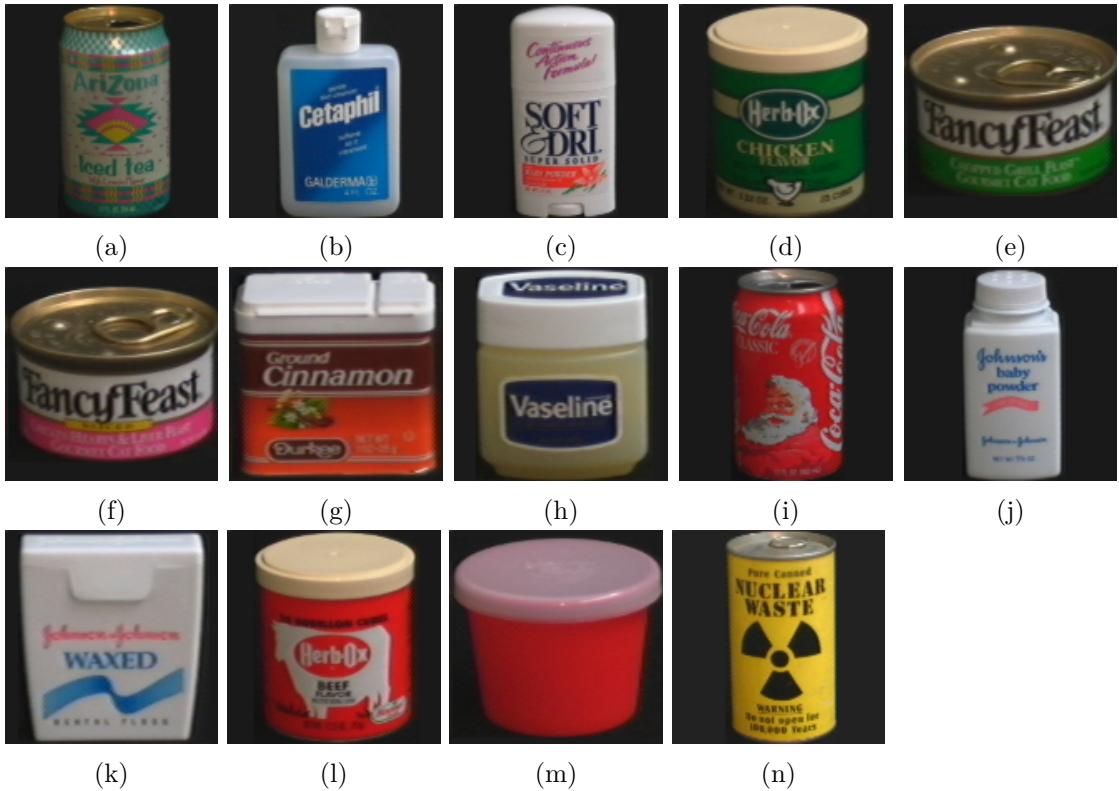


Figure 5.2: The 14 selected images from the Columbia Object Image Library (COIL-100)

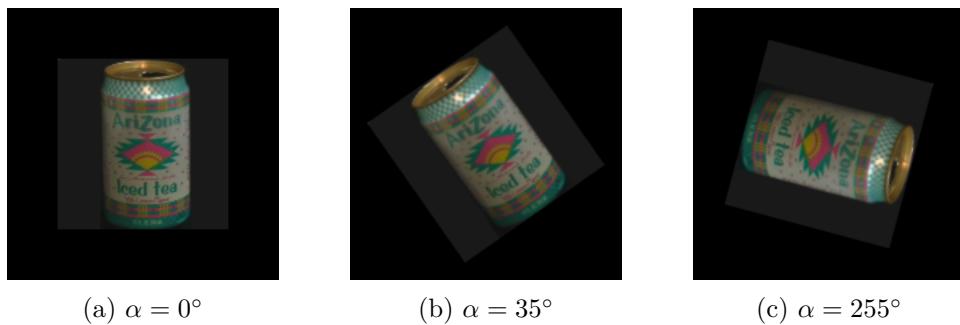


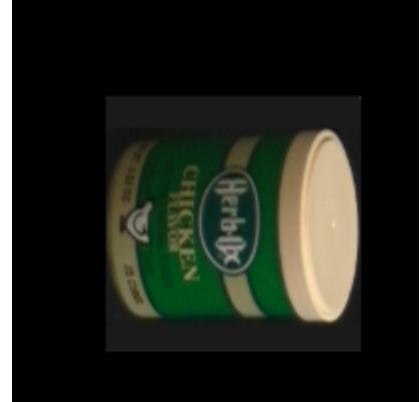
Figure 5.3: Some extended and rotated images from COIL



(a) $\alpha = 0^\circ, \lambda = 1$



(b) $\alpha = 150^\circ, \lambda = 0.5$



(c) $\alpha = 270^\circ, \lambda = 1.5$

Figure 5.4: Some RST transformed images from COIL. All images are translated by $\Delta x = -11, \Delta y = 9$

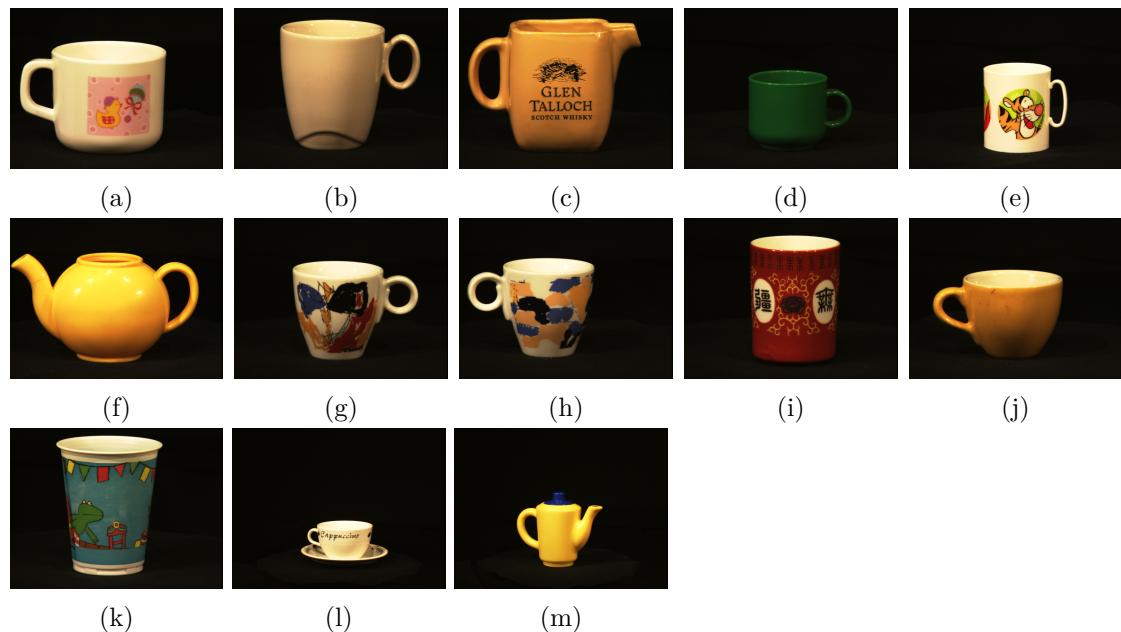


Figure 5.5: The 13 selected images from the Amsterdam Library of Object Images (ALOI)

5.2 Invariance test

In order to test quaternion Zernike moment invariants with respect to rotation, scaling and translation, the QZMIs of order 1 to 4 were calculated for a given image and all of its RST transformations. Then, the modulus of these QZMIs was calculated, as well as the mean (μ), standard deviation (σ) and $\frac{\sigma}{\mu}$ for the same moment of all transformed images.

Results

The moduli of the QZMIs for the transformed images shown on Figure 5.6 is shown in Table 5.1 for the old method of discretization and in Table 5.2 for the new, proposed method of discretization. The coefficient of variation ($\frac{\sigma}{\mu}$) shows that using both methods, the moments are invariant to RST transformation. The only rows where $\frac{\sigma}{\mu}$ is higher are the ones where the modulus of the moment is very close to zero, and thus small numerical errors impact this number significantly. Comparing the two methods, the proposed one yields slightly lower values for the coefficient of variation for all moments.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 5.6: The images with different rotation and scale, which are used to test the invariance of the methods.

	Fig.5.6a	Fig.5.6b	Fig.5.6c	Fig.5.6d	Fig.5.6e	Fig.5.6f	$\frac{\sigma}{\mu}$
$ \bar{\Psi}_{1,1}^1 $	1.50e-2	1.58e-2	1.54e-2	1.61e-2	1.58e-2	1.49e-2	3.73%
$ \bar{\Psi}_{2,0}^0 $	2.965	2.964	2.964	2.963	2.964	2.965	0.028%
$ \bar{\Psi}_{2,2}^0 $	8.793	8.785	8.789	8.783	8.786	8.794	0.057%
$ \bar{\Psi}_{2,2}^2 $	1.50e-4	1.65e-4	1.57e-4	1.69e-4	1.65e-4	1.47e-4	6.87%
$ \bar{\Psi}_{3,1}^1 $	5.91e-2	6.25e-2	6.09e-2	6.34e-2	6.22e-2	5.89e-2	3.71%
$ \bar{\Psi}_{3,3}^1 $	0.233	0.247	0.241	0.250	0.246	0.233	3.69%
$ \bar{\Psi}_{3,3}^3 $	1.43e-6	1.61e-6	1.50e-6	1.67e-6	1.62e-6	1.38e-6	9.40%
$ \bar{\Psi}_{4,0}^0 $	4.827	4.821	4.824	4.820	4.822	4.828	0.086%
$ \bar{\Psi}_{4,2}^0 $	14.316	14.291	14.302	14.284	14.292	14.318	0.114%
$ \bar{\Psi}_{4,2}^2 $	7.39e-4	8.13e-4	7.74e-4	8.35e-4	8.12e-4	7.26e-4	6.85%
$ \bar{\Psi}_{4,4}^0 $	23.309	23.249	23.276	23.232	23.251	23.314	0.171%
$ \bar{\Psi}_{4,4}^2 $	3.64e-3	4.00e-3	3.81e-3	4.11e-3	4.00e-3	3.58e-3	6.83%
$ \bar{\Psi}_{4,4}^4 $	1.28e-8	1.52e-8	1.39e-8	1.59e-8	1.51e-8	1.25e-8	12.00%

Table 5.1: The modulus of QZMIs using the old method for discretization. Note that $\frac{\sigma}{\mu}$ was calculated using the QZMIs for all transformation of the image, not just the values shown in the table.

	Fig.5.6a	Fig.5.6b	Fig.5.6c	Fig.5.6d	Fig.5.6e	Fig.5.6f	$\frac{\sigma}{\mu}$
$ \bar{\Psi}_{1,1}^1 $	1.49e-2	1.58e-2	1.54e-2	1.60e-2	1.57e-2	1.49e-2	3.72%
$ \bar{\Psi}_{2,0}^0 $	2.965	2.964	2.964	2.963	2.964	2.965	0.028%
$ \bar{\Psi}_{2,2}^0 $	8.793	8.785	8.789	8.783	8.786	8.793	0.056%
$ \bar{\Psi}_{2,2}^2 $	1.49e-4	1.64e-4	1.55e-4	1.68e-4	1.63e-4	1.47e-4	6.82%
$ \bar{\Psi}_{3,1}^1 $	5.90e-2	6.25e-2	6.08e-2	6.33e-2	6.21e-2	5.89e-2	3.70%
$ \bar{\Psi}_{3,3}^1 $	0.233	0.247	0.240	0.250	0.245	0.233	3.68%
$ \bar{\Psi}_{3,3}^3 $	1.41e-6	1.61e-6	1.48e-6	1.65e-6	1.60e-6	1.37e-6	9.32%
$ \bar{\Psi}_{4,0}^0 $	4.828	4.821	4.824	4.820	4.822	4.828	0.085%
$ \bar{\Psi}_{4,2}^0 $	14.317	14.291	14.304	14.286	14.293	14.318	0.113%
$ \bar{\Psi}_{4,2}^2 $	7.35e-4	8.13e-4	7.68e-4	8.29e-4	8.07e-4	7.25e-4	6.80%
$ \bar{\Psi}_{4,4}^0 $	23.312	23.249	23.279	23.236	23.254	23.314	0.170%
$ \bar{\Psi}_{4,4}^2 $	3.62e-3	4.00e-3	3.79e-3	4.09e-3	3.98e-3	3.58e-3	6.78%
$ \bar{\Psi}_{4,4}^4 $	1.28e-8	1.52e-8	1.37e-8	1.56e-8	1.50e-8	1.24e-8	11.94%

Table 5.2: The modulus of QZMIs using the new method for discretization. Note that $\frac{\sigma}{\mu}$ was calculated using the QZMIs for all transformation of the image, not just the values shown in the table.

5.3 Image reconstruction

As described in Section 2.3, the quaternion Zernike moments of an image can be used to approximately reconstruct the original image using the formulas in (2.7). This reconstruction requires the computation of QZMs of up to a finite degree M .

In order to reconstruct the discrete image, formula

$$f(r_{x,y}, \theta_{x,y}) \approx \sum_{n=0}^M \sum_{m=-n}^n Z_{n,m}^R(f) R_{n,m}(r_{x,y}) e^{\mu m \theta_{x,y}}$$

was used for each pixel with image coordinates (x, y) , where $(r_{x,y}, \theta_{x,y})$ are the polar coordinates obtained by performing the linear transformation of the image onto the unit disk, using the transformation shown on Figure 2.1 (tf_1) for the old method and the transformation shown on Figure 2.2 (tf_2) for the new one. The reason for this difference in transformation is that for the proposed discrete orthogonal points system, the interpolated pixel values are calculated using tf_2 , while conventionally for (quaternion) Zernike moments, tf_1 is used [2].

To measure the error of the reconstruction the normalized mean squared error (ε^2) was used. If $f(x, y)$ is the original and $\hat{f}(x, y)$ is the reconstructed image, both with size $N \times N$, then the normalized mean squared error is defined as:

$$\varepsilon^2 = \frac{\sum_{x=1}^N \sum_{y=1}^N |f(x, y) - \hat{f}(x, y)|^2}{\sum_{x=1}^N \sum_{y=1}^N |f(x, y)|^2}.$$

In the cases, where tf_2 is used only the part of the image falling inside the unit circle is reconstructed and thus the mean squared error is calculated over only this part of the image.

For the new method of discretization the number of points on the unit disk was chosen to be approximately the same as the number of pixels falling inside the inscribed circle of the image.

Results

Image reconstruction was performed for both the Lenna and the Pepper images [51], using image sizes ranging from 64×64 up to 256×256 . Depending on the size of the

M	50	100	150	250	350
old method ε^2	0.02659	0.01341	0.00868	0.00428	0.00279
new method ε^2	0.01611	0.00790	0.00463	0.00190	0.00238
change	-39.4%	-41.1%	-46.7%	-55.6%	-14.7%

Table 5.3: Comparison of the normalized mean squared errors between the two method, for the 256×256 Lenna image.

image, QZMs of up to degree 350 were used reconstruct the image. However, in the case of smaller images, for example a 64×64 image, only QZMs of up to 100 degree could be used, as using higher degrees would result in trying to extract more information from the original image than there is information contained in the pixel values, thus increasing the error of reconstruction. This phenomenon is visible, for example on Figure 5.8 for the 64×64 Lenna, $M = 100$ case.

Figure 5.7 shows some of the reconstructed images and their normalized mean squared error when using the old method of discretization, while Figure 5.8 shows the same data using the new method.

Comparing the error of reconstruction between the two methods, using the discrete orthogonal points system provides much lower normalized mean squared errors for almost all levels of reconstruction. Table 5.3 shows the comparison between the ε^2 values and the change in the error when using the proposed method instead of the old one. The decrease in the error of reconstruction is significant for both low and high maximal degrees of QZMs.

Due to the lower number of points used by the second method (because of the different transformation of the image onto the unit disk) the previously described increase in reconstruction error occurs for lower M s than in the original method.

M	Lenna 64 × 64	Lenna 128 × 128	Lenna 256 × 256	Pepper 256 × 256
Original				
M = 50				
	0.01257	0.01948	0.02659	0.03777
M = 100				
	0.00468	0.00719	0.01341	0.01596
M = 150				
	0.00388	0.00868	0.00885	
M = 250				
	0.00428	0.00378		
M = 350				
	0.00279	0.00253		

Figure 5.7: Reconstructed images using the old method, with the normalized mean squared error shown below each image.

M	Lenna 64 × 64	Lenna 128 × 128	Lenna 256 × 256	Pepper 256 × 256
Original				
M = 50				
	0.00380	0.00901	0.01611	0.01778
M = 100				
	0.01181	0.00246	0.00790	0.00681
M = 150				
		0.00152	0.00463	0.00349
M = 250				
			0.00190	0.00131
M = 350				
			0.00238	0.00229

Figure 5.8: Reconstructed images using the proposed new method, with the normalized mean squared error shown below each image.

5.4 Image recognition

In order to test image recognition capabilities, the COIL-100 [9] and ALOI [10] images and the RST transformed sets of images were used. The exact parameters for the transformations performed to obtain these sets of images is described in Section 5.1. The goal of the image recognition test is to see what percentage of the transformed images can each method correctly identify by comparing their moment invariants to the ones of the original, non-transformed images.

To recognize an image, first the QZMIs have to be calculated. In this thesis, we used QZMIs of up to degree 4, but not all possible QZMIs were used. The selected QZMIs were: $\bar{\Psi}_{1,1}^1, \bar{\Psi}_{2,0}^0, \bar{\Psi}_{2,2}^2, \bar{\Psi}_{3,1}^1, \bar{\Psi}_{3,3}^3, \bar{\Psi}_{4,0}^0, \bar{\Psi}_{4,2}^2, \bar{\Psi}_{4,4}^4$. These 8 quaternion valued invariants contain a total of 20 real valued invariants, since while each quaternion could provide of 4 real invariants, the QZMIs $\bar{\Psi}_{n,k}^m$ with $n = k$ necessarily have $\text{Im } \bar{\Psi}_{n,n}^m = 0$. This follows directly from the definition (see Section 2.5):

$$\bar{\Psi}_{n,n}^m = \bar{L}_{n,m}^R(f)(\bar{L}_{n,m}^R(f))^* = \left| \bar{L}_{n,m}^R(f) \right|^2 \in \mathbb{R}.$$

Thus from the selected 8 QZMIs four provide a single real-valued invariant and another four provide 4 real-valued invariants. These 20 real invariants are then used to construct a vector I of length 20. This vector is normalized using the method presented by Suk and Flusser [21].

$$I_k = \text{sgn}(I_k) |I_k|^{\frac{1}{2}} \quad (k = 1, 2, \dots, 20).$$

This invariant vector is calculated for an RST transformed image and all of the original images. Then the minimum Euclidean distance is used to choose from the original images. The recognition algorithm classifies the transformed image as this chosen image.

Noise generation

To test robustness against noise the tests were also performed with different levels of real-valued Gaussian noise added to all images. The parameters of the Gaussian noise were as follows: the mean of the distribution was always at 0, while standard deviation (σ) values from 1 up to 60 were used for the QZMIs and standard deviation ranging from 40 to 120 was used to test the QZMRIs. QZMRIs are more robust against noise than QZMIs, so higher noise values could be used. Instead of using Gaussian noise, for some test cases salt-and-pepper noise was added with densities (p) ranging from 0.2% up to 15% for the QZMIs and ranging from 5% to 30% for the QZMRIs. Some examples for both types of noise are shown on Figure 5.9.

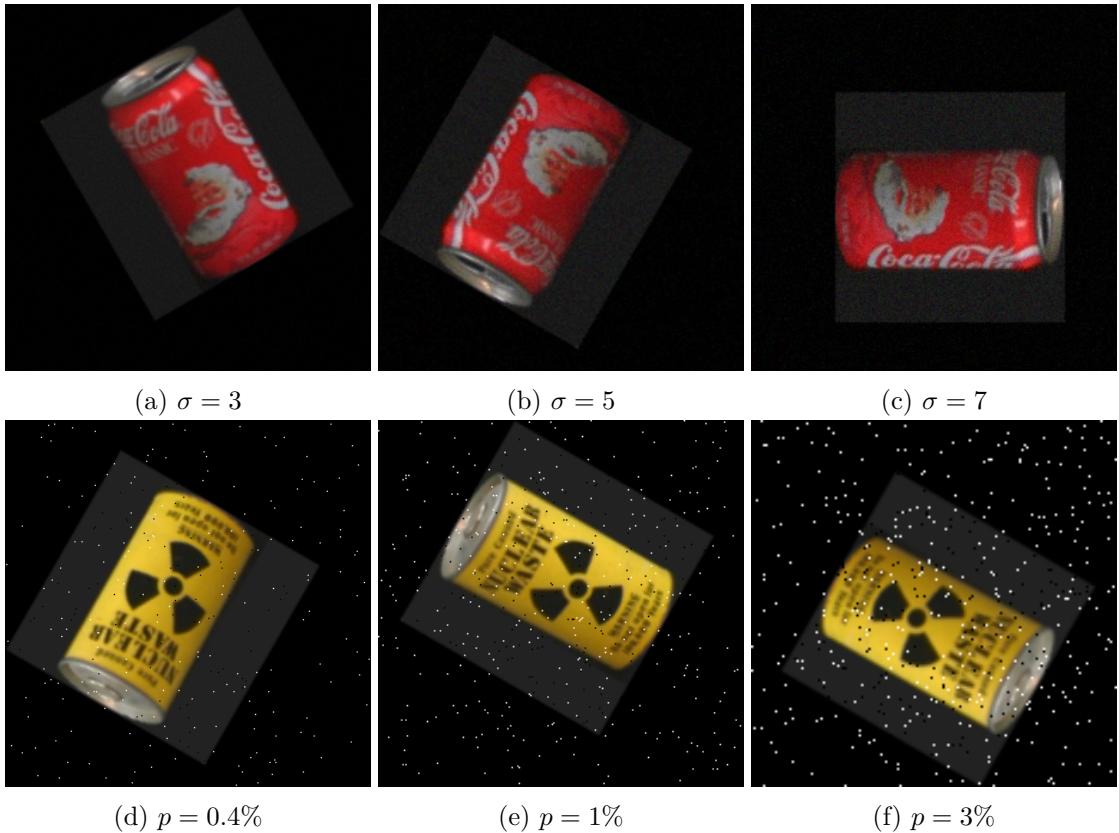


Figure 5.9: Some test images with Gaussian noise (top row) or salt-and-pepper noise (bottom row) with different parameters added to them.

The tests were performed directly using the raw, noisy images, without any kind of filtering applied to the image. The goal was to see the robustness of these methods against noise.

Test cases

The recognition tests were performed using both the old and the proposed method for discretization. Furthermore, the new method was tested with two different N values for creating the discrete orthogonal system of $8N^2$ points.

In the first case N was chosen such that the total number of points in the system should

be approximately the same as the pixels of the image falling inside its inscribed circle.

$$\begin{aligned} N &\in \mathbb{N} \\ 8N^2 &\approx n^2 \frac{\pi}{4} \\ N &= \left\lceil 2n\sqrt{\pi} \right\rceil. \end{aligned}$$

where the size of the image is $n \times n$. Based on the interpolating methods described in Section 4.3 this means that bilinear interpolation should be used.

In the other case N was chosen such that the number of points is close to the minimum required to achieve discrete orthogonality of moments up to degree 4. In this case $N = 10$ was chosen. Since the number of points is far less than the number of pixels, based on Section 4.3 the interpolation should be done using the integral interpolation formula.

Note that for the old method, the number of points used is the same as the number of pixels in the image.

Three sets of transformed images were tested, which were generated as described in Section 5.1:

- COIL-100 rotated (1008 images)
- COIL-100 rotated, scaled, translated (1176 images)
- ALOI rotated, scaled, translated (1092 images)

For the set where only rotation was applied to the images, instead of using QZMIs the rotation invariant QZMRIs were used.

Results

When the images have Gaussian noise, the new method with the higher number of points performs the best for all levels of noise, far outperforming the original method in recognition capabilities. The rate of recognition for Gaussian noise in case of the RST transformed image sets is shown in Table 5.4. The recognition rate of the new method remains relatively high (around 80%) even for high noise values, while the recognition rate of the original method drops significantly (below 20% in some cases).

When using only the minimal possible number of points in the new method, for all noise levels the recognition rate remains roughly around the same level as with the original

Image set	Noise stdev.	Old method (%)	New method many points (%)	New method few points (%)
COIL - RST	No noise	99.06	99.15	98.21
	1	98.98	99.49	98.81
	2	98.98	99.74	98.81
	3	98.55	99.83	98.04
	5	95.15	99.49	94.64
	7	95.15	98.72	91.67
	9	76.87	98.47	89.20
	40	52.89	88.52	51.87
	50	48.21	84.10	45.07
	60	41.58	85.80	39.12
ALOI - RST	No noise	99.91	100.00	94.60
	1	94.51	99.08	86.63
	2	84.89	93.13	86.35
	3	78.85	88.55	74.81
	5	72.07	93.31	58.24
	7	63.28	94.23	61.81
	9	55.04	94.32	48.81
	40	18.41	90.84	15.29
	50	19.32	82.51	15.93
	60	13.19	84.89	13.83

Table 5.4: Percentage of images recognized correctly by QZMIs in the case of using the RST transformed image sets with added Gaussian noise.

method, but the computation required to achieve such levels of image recognition is much lower because of the lower number of points.

The same observation can be made about the QZMRIs used to recognize the rotated images. Even for extremely high noise values, the recognition rate of the new method remains well above 90%. The results for the QZMRIs are shown in Table 5.5.

The reason for such differences between the old and the new methods is that the old method uses a non-orthogonal discretization, which means some redundancy occurs among the QZMs. This leads to the value of the added increasing when these QZMs are multiplied to construct the QZMIs. On the other hand, the new method uses a discrete orthogonal system, which means no redundancy between the QZMs and thus it more robust against Gaussian noise.

When salt-and-pepper noise is added to the images, the recognition capabilities of both methods are high, but no clear difference is visible between them. Even using the minimal possible number of points in the new method, the recognition rates are almost the same as with the other two methods. These same observation can be made about the recognition capabilities of the QZMRIs. The results for salt-and-pepper noise are shown for QZMIs and QZMRIs in Table 5.6 and Table 5.5 respectively.

The reason for no significant difference between the methods in the case of salt-and-pepper noise is that this kind of noise adds a high frequency component to the image. Choosing only moments with low order for image recognition behaves as a low-pass filter, since these moments are most sensitive to low frequency components. Thus both methods are able to handle salt-and-pepper noise well.

Noise type	Noise param.	Old method (%)	New method many points (%)	New method few points (%)
No noise		100.00	100.00	100.00
Gauss	40	91.37	99.90	92.56
	50	86.51	100.00	94.44
	60	84.42	99.60	93.35
	70	80.85	99.90	83.93
	80	76.98	98.12	80.45
	90	75.79	99.01	83.83
	100	64.98	98.91	79.46
	110	64.78	97.62	69.94
	120	68.55	96.23	72.12
Salt	5	100.00	100.00	
	10	100.00	100.00	
	15	100.00	100.00	
	20	100.00	100.00	
	25	100.00	100.00	
	30	100.00	100.00	

Table 5.5: Percentage of images recognized correctly by QZMRIs in the case of using the rotated COIL image set with either Gaussian or salt-and-pepper noise. The noise parameter means the standard deviation in case of the Gaussian noise, and the density in case of the salt-and-pepper noise.

Image set	Noise density	Old method (%)	New method many points (%)	New method few points (%)
COIL - RST	No noise	99.06	99.15	98.21
	0.2	99.66	99.32	94.98
	0.4	99.91	99.74	99.15
	0.6	99.91	99.91	99.40
	1	98.98	99.91	99.66
	2	99.66	93.96	99.74
	3	99.40	99.40	96.34
	5	97.87	94.90	97.87
	10	99.91	93.03	98.72
	15	99.91	93.20	97.87
ALOI - RST	No noise	99.91	100.00	94.60
	0.2	88.64	90.75	78.11
	0.4	86.08	91.30	80.95
	0.6	83.97	90.11	89.19
	1	95.97	94.60	94.51
	2	98.44	94.96	95.97
	3	97.61	96.06	97.25
	5	97.99	97.25	89.56
	10	98.44	87.27	93.22
	15	93.50	91.30	97.71

Table 5.6: Percentage of images recognized correctly by QZMIs in the case of using the RST transformed image sets with added salt-and-pepper noise.

5.5 Template matching

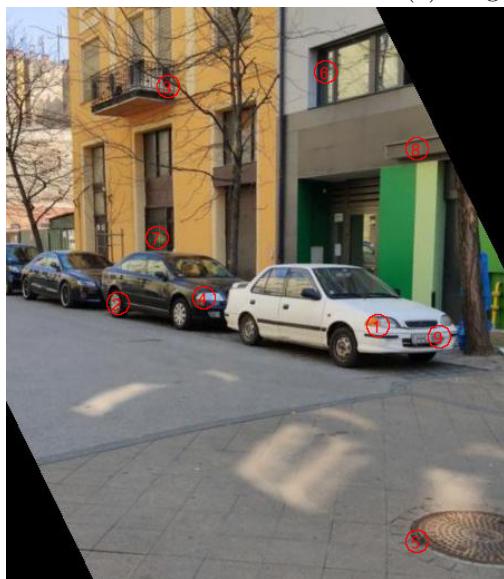
This final test aims to present some possible application of the pattern matching capabilities of the QZMIs. Some pictures were taken using a the camera on a Xiaomi Mi 9 smartphone with autofocus enabled. The images were taken of the same scene but with different focus and different rotation of the camera.

A total of 9 circles with radii of 10 pixels were chosen so that they represent some unique area on the pictures. Then, on another picture taken with different rotation and focus, after determining the scaling factor between the two images, a sliding circular window was moved across the second image. The invariant vector described in the image recognition test was constructed for each window, and then the minimal Euclidean distance was used to find each area of the original image on the second image.

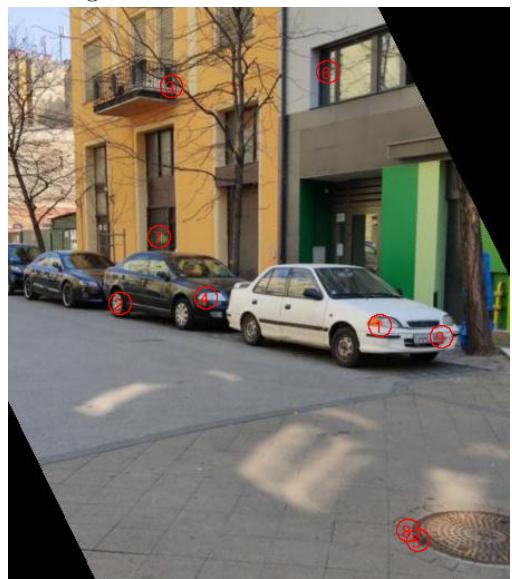
The original image and the results of both methods are shown on Figure 5.10. Both methods managed to correctly find 8 out of the 9 templates on the other image. Neither managed to correctly locate template number 8.



(a) Original image



(b) Old method



(c) New method

Figure 5.10: The original image with the templates and the result of both methods.

Chapter 6

Conclusion

In this chapter we summarize the work and results presented in this thesis. We also present a short overview of further possibilities based on this work.

We have constructed a points system on the unit disk, over which the quaternion extension of the Zernike functions is discrete orthogonal. Using this method of discretization, the quaternion Zernike moments are more robust to noise than with the previously used method.

Many tests have been performed on large sets of images to verify and quantify the improvements of the method. First, the invariance properties of the QZMIs have been verified empirically using the proposed method.

By comparing the image reconstruction capabilities of the original and the proposed method, we found that the mean square error of reconstruction can decrease significantly, by more than 50% in some cases, when using the proposed method.

Significant improvements in image recognition have also been achieved by the new method, especially under highly noisy environments. With respect to Gaussian noise the new method is much more robust, achieving a recognition rate of more than 80% even for extreme noise values, where the original method only achieved a rate of recognition of around 15%. The reason for this improvement is that due to the discrete orthogonality property of the new method, there is no redundancy between different moments.

With respect to salt-and-pepper noise, no significant difference could be determined between the methods, since this kind of noise adds a very high frequency component to the image, which is filtered by using only moments with low orders in both methods.

We have also found that in order to achieve almost the same recognition rate with the new method as the original one, the number of points in the system can be reduced to almost the minimum number required to still achieve discrete orthogonality. This reduces the computational costs significantly.

6.1 Future possibilities

One possibility for future work is to employ the techniques described in this thesis in some applications, which currently use other Zernike moment based methods.

It is also possible to utilize the techniques described in this thesis to try and improve other quaternion moment invariant based methods, such as the quaternion Fourier-Mellin moments [1].

Finally, the methods described could be further generalized to three dimensional space, where possible applications include pattern recognition in point clouds produced by LiDAR sensors [52].

Acknowledgment

The project was made possible by the support of the European Union and the co-funding of the European Social Fund (EFOP-3.6.3-VEKOP-16-2017-00001).



Bibliography

- [1] Li-Qiang Guo and Ming Zhu. Quaternion fourier–mellin moments for color images. *Pattern Recognition*, 44(2):187 – 195, 2011. ISSN 0031-3203. doi: <https://doi.org/10.1016/j.patcog.2010.08.017>. URL <http://www.sciencedirect.com/science/article/pii/S0031320310004036>.
- [2] Beijing Chen, Huazhong Shu, Hui Zhang, Gang Chen, Christine Toumoulin, Jean-Louis Dillenseger, and Limin Luo. Quaternion zernike moments and their invariants for color image analysis and object recognition. *Signal Processing*, 92:308–318, 02 2012. doi: 10.1016/j.sigpro.2011.07.018.
- [3] Zhuhong Shao, Huazhong Shu, Jiasong Wu, Beijing Chen, and Jean Louis Coatrieux. Quaternion bessel–fourier moments and their invariant descriptors for object reconstruction and recognition. *Pattern Recognition*, 47(2):603 – 611, 2014. ISSN 0031-3203. doi: <https://doi.org/10.1016/j.patcog.2013.08.016>. URL <http://www.sciencedirect.com/science/article/pii/S0031320313003373>.
- [4] Hongqing Zhu, Yan Yang, Zhiguo Gui, Yu Zhu, and Zhihua Chen. Image analysis by generalized chebyshev–fourier and generalized pseudo-jacobi–fourier moments. *Pattern Recognition*, 51:1 – 11, 2016. ISSN 0031-3203. doi: <https://doi.org/10.1016/j.patcog.2015.09.018>. URL <http://www.sciencedirect.com/science/article/pii/S0031320315003490>.
- [5] Yi Hsien Lin and Chin-Hsing Chen. Template matching using the parametric template vector with translation, rotation and scale invariance. *Pattern Recognition*, 41(7):2413–2421, July 2008. ISSN 0031-3203. doi: 10.1016/j.patcog.2008.01.017.
- [6] S.O. Belkasim, M. Shridhar, and M. Ahmadi. Pattern recognition with moment invariants: A comparative study and new results. *Pattern Recognition*, 24(12):1117 – 1138, 1991. ISSN 0031-3203. doi: [https://doi.org/10.1016/0031-3203\(91\)90140-Z](https://doi.org/10.1016/0031-3203(91)90140-Z). URL <http://www.sciencedirect.com/science/article/pii/003132039190140Z>.
- [7] Mohammed Saaidia, Lelandais Sylvie, and Vincent Vigneron. Face detection by neural network trained with zernike moments. *Signal Processing*, 01 2007.

- [8] B. Chen, H. Shu, H. Zhang, G. Chen, and L. Luo. Color image analysis by quaternion zernike moments. In *2010 20th International Conference on Pattern Recognition*, pages 625–628, 2010.
- [9] S. A. Nene, S. K. Nayar, and H. Murase. Columbia Object Image Library (COIL-100). *Technical Report CUCS-006-96*, 1996.
- [10] J.M. Geusebroek, G.J. Burghouts, and A.W.M. Smeulders. ALOI: Amsterdam Library of Object Images. *International Journal of Computer Vision*, 61(1):103–122, 2005. URL <http://aloi.science.uva.nl/>.
- [11] Feng Zhang, Shang-qian Liu, Da-bao Wang, and Wei Guan. Aircraft recognition in infrared image using wavelet moment invariants. *Image and Vision Computing*, 27: 313–318, 03 2009. doi: 10.1016/j.imavis.2008.08.007.
- [12] Florica Mindru, Tinne Tuytelaars, Luc Van Gool, and Theo Moons. Moment invariants for recognition under changing viewpoint and illumination. *Computer Vision and Image Understanding*, 94(1):3 – 27, 2004. ISSN 1077-3142. doi: <https://doi.org/10.1016/j.cviu.2003.10.011>. URL <http://www.sciencedirect.com/science/article/pii/S1077314203001930>. Special Issue: Colour for Image Indexing and Retrieval.
- [13] Yu-Dong Zhang, Shui-Hua Wang, Xiao-Jun Yang, Zheng-Chao Dong, Ge Liu, Preetha Phillips, and Ti-Fei Yuan. Pathological brain detection in mri scanning by wavelet packet tsallis entropy and fuzzy support vector machine. *Springer-Plus*, 4:716, 2015. ISSN 2193-1801. doi: 10.1186/s40064-015-1523-4. URL <https://europepmc.org/articles/PMC4656268>.
- [14] von F. Zernike. Beugungstheorie des schneidenverfahrens und seiner verbesserten form, der phasenkontrastmethode. *Physica*, 1(7):689 – 704, 1934. ISSN 0031-8914. doi: [https://doi.org/10.1016/S0031-8914\(34\)80259-5](https://doi.org/10.1016/S0031-8914(34)80259-5). URL <http://www.sciencedirect.com/science/article/pii/S0031891434802595>.
- [15] Margit Pap and Ferenc Schipp. Discrete orthogonality of zernike functions. *Mathematica Pannonica*, 16, 01 2005.
- [16] G. Szegő. *Orthogonal Polynomials*. American Mathematical Society Colloquium publications 23, 1975.
- [17] James Wyant and Katherine Creath. Basic wavefront aberration theory for optical metrology. *Appl Optics Optical Eng*, 11, 01 1992.
- [18] Luis Alberto Vieira de Carvalho and Jarbas Caiado de Castro. Preliminary results of an instrument for measuring the optical aberrations of the human eye. 2003.
- [19] Victor L Genberg. Optical Surface Evaluation. In Lester M. Cohen, editor, *Structural Mechanics of Optical Systems I*, volume 0450, pages 81 – 87. International

Society for Optics and Photonics, SPIE, 1984. doi: 10.1117/12.939270. URL <https://doi.org/10.1117/12.939270>.

- [20] A. Khotanzad and Y. H. Hong. Invariant image recognition by zernike moments. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 12(5):489–497, 1990.
- [21] Tomáš Suk and Jan Flusser. Affine moment invariants of color images. In Xiaoyi Jiang and Nicolai Petkov, editors, *Computer Analysis of Images and Patterns*, pages 334–341, Berlin, Heidelberg, 2009. Springer Berlin Heidelberg. ISBN 978-3-642-03767-2.
- [22] William Rowan Hamilton. *Elements of Quaternions*. Longmans Green, London, U.K., 1866.
- [23] T. A. Ell and S. J. Sangwine. Hypercomplex fourier transforms of color images. *IEEE Transactions on Image Processing*, 16(1):22–35, 2007.
- [24] Chee-Way Chong, P. Raveendran, and R. Mukundan. A comparative analysis of algorithms for fast computation of zernike moments. *Pattern Recognition*, 36(3):731 – 742, 2003. ISSN 0031-3203. doi: [https://doi.org/10.1016/S0031-3203\(02\)00091-2](https://doi.org/10.1016/S0031-3203(02)00091-2). URL <http://www.sciencedirect.com/science/article/pii/S0031320302000912>.
- [25] Chee-Way Chong, P. Raveendran, and R. Mukundan. Translation invariants of zernike moments. *Pattern Recognition*, 36(8):1765 – 1773, 2003. ISSN 0031-3203. doi: [https://doi.org/10.1016/S0031-3203\(02\)00353-9](https://doi.org/10.1016/S0031-3203(02)00353-9). URL <http://www.sciencedirect.com/science/article/pii/S0031320302003539>.
- [26] Y. N. Li. Quaternion polar harmonic transforms for color images. *IEEE Signal Processing Letters*, 20(8):803–806, 2013.
- [27] Liqiang Guo, Ming Dai, and Ming Zhu. Quaternion moment and its invariants for color object classification. *Information Sciences*, 273:132 – 143, 2014. ISSN 0020-0255. doi: <https://doi.org/10.1016/j.ins.2014.03.037>. URL <http://www.sciencedirect.com/science/article/pii/S0020025514003211>.
- [28] Zuhong Shao, Huazhong Shu, Jiasong Wu, Beijing Chen, and Jean Louis Coatrieux. Quaternion bessel-fourier moments and their invariant descriptors for object reconstruction and recognition. *Pattern Recognition*, 47(2):603 – 611, 2014. ISSN 0031-3203. doi: <https://doi.org/10.1016/j.patcog.2013.08.016>. URL <http://www.sciencedirect.com/science/article/pii/S0031320313003373>.
- [29] Wang Xiang-yang, Li Wei-yi, Yang Hong-ying, Niu Pan-pan, and Li Yong-wei. Invariant quaternion radial harmonic fourier moments for color image retrieval. *Optics & Laser Technology*, 66:78 – 88, 2015. ISSN 0030-3992. doi: <https://doi.org/10.1016/j.optlastec.2014.07.020>. URL <http://www.sciencedirect.com/science/article/pii/S003039921400200X>.

- [30] Chandan Singh and Jaspreet Singh. Quaternion generalized chebyshev-fourier and pseudo-jacobi-fourier moments for color object recognition. *Optics & Laser Technology*, 106:234 – 250, 2018. ISSN 0030-3992. doi: <https://doi.org/10.1016/j.optlastec.2018.03.033>. URL <http://www.sciencedirect.com/science/article/pii/S0030399217316365>.
- [31] Tengfei Yang, Jianfeng Ma, Yinbin Miao, Xuan Wang, Bin Xiao, Bing He, and Qian Meng. Quaternion weighted spherical bessel-fourier moment and its invariant for color image reconstruction and object recognition. *Information Sciences*, 505:388 – 405, 2019. ISSN 0020-0255. doi: <https://doi.org/10.1016/j.ins.2019.07.089>. URL <http://www.sciencedirect.com/science/article/pii/S002002551930708X>.
- [32] Simon Liao and Mirek Pawlak. On the accuracy of zernike moments for image analysis. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 20: 1358 – 1364, 01 1999. doi: 10.1109/34.735809.
- [33] Mirek Pawlak and Simon Liao. On the recovery of a function on a circular domain. *Information Theory, IEEE Transactions on*, 48:2736 – 2753, 11 2002. doi: 10.1109/TIT.2002.802627.
- [34] Y. Xin, M. Pawlak, and S. Liao. Accurate computation of zernike moments in polar coordinates. *IEEE Transactions on Image Processing*, 16(2):581–587, 2007.
- [35] Khalid Hosny and Mohamed Darwish. Invariant color images representation using accurate quaternion legendre–fourier moments. *Pattern Analysis and Applications*, 07 2018. doi: 10.1007/s10044-018-0740-1.
- [36] Khalid Hosny and Mohamed Darwish. New set of quaternion moments for color images representation and recognition. *Journal of Mathematical Imaging and Vision*, 01 2018. doi: 10.1007/s10851-018-0786-0.
- [37] Chunpeng Wang, Wang Xing-yuan, and Xia Zhi-qiu. Geometrically invariant image watermarking based on fast radial harmonic fourier moments. *Signal Processing: Image Communication*, 45, 03 2016. doi: 10.1016/j.image.2016.03.007.
- [38] Yunan Liu, Shanshan Zhang, Guangyu Li, Houjun Wang, and Jian Yang. Accurate quaternion radial harmonic fourier moments for color image reconstruction and object recognition. *Pattern Analysis and Applications*, pages 1–17, 04 2020. doi: 10.1007/s10044-020-00877-6.
- [39] Raúl Castro-Ortega, Carina Toxqui-Quitl, Alfonso Padilla-Vivanco, Jose Francisco Solís-Villarreal, and Eber Enrique Orozco-Guillén. Zernike moment invariants for hand vein pattern description from raw biometric data. *Journal of Electronic Imaging*, 28(5):1 – 11, 2019. doi: 10.1117/1.JEI.28.5.053019. URL <https://doi.org/10.1117/1.JEI.28.5.053019>.

- [40] Hamid Shojanazeri, wan Azizun wan adnan, Sharifah Ahmad, and Somayeh Rahimipour. Authentication of images using zernike moment watermarking. *Multimedia Tools and Applications*, 76, 11 2015. doi: 10.1007/s11042-015-3018-2.
- [41] Nitin Singhal, Young-Yoon Lee, Chang-Su Kim, and Sang-Uk Lee. Robust image watermarking using local zernike moments. *Journal of Visual Communication and Image Representation*, 20(6):408 – 419, 2009. ISSN 1047-3203. doi: <https://doi.org/10.1016/j.jvcir.2009.04.002>. URL <http://www.sciencedirect.com/science/article/pii/S1047320309000546>.
- [42] Hyung Shin Kim and Heung-Kyu Lee. Invariant image watermark using zernike moments. *IEEE Trans. Cir. and Sys. for Video Technol.*, 13(8):766–775, August 2003. ISSN 1051-8215. doi: 10.1109/TCSVT.2003.815955. URL <https://doi.org/10.1109/TCSVT.2003.815955>.
- [43] Stephan Zheng, Yang Song, Thomas Leung, and Ian Goodfellow. Improving the robustness of deep neural networks via stability training. 06 2016. doi: 10.1109/CVPR.2016.485.
- [44] Mengchen Liu, Shixia Liu, Hang Su, Kelei Cao, and Jun Zhu. Analyzing the noise robustness of deep neural networks. pages 60–71, 10 2018. doi: 10.1109/VAST.2018.8802509.
- [45] Luis Carvalho. Preliminary results of neural networks and zernike polynomials for classification of videokeratography maps. *Optometry and vision science : official publication of the American Academy of Optometry*, 82:151–8, 03 2005. doi: 10.1097/01.OPX.0000153193.41554.A1.
- [46] Python Software Foundation. The python language reference. <https://docs.python.org/3/reference/>, 2020. [Accessed: 2020.05.06.]
- [47] The SciPy community. Numpy v1.18 manual. <https://numpy.org/doc/stable/>, 2020. [Accessed: 2020.05.06.]
- [48] Anaconda Inc. et al. Numba reference manual. <http://numba.pydata.org/numba-doc/latest/reference/index.html>, 2020. [Accessed: 2020.05.06.]
- [49] Alex Clark et al. Pillow reference manual. <https://pillow.readthedocs.io/en/stable/>, 2020. [Accessed: 2020.05.06.]
- [50] Andreas Glaser, Xiangtao Liu, and Vladimir Rokhlin. A fast algorithm for the calculation of the roots of special functions. *SIAM J. Scientific Computing*, 29: 1420–1438, 01 2007. doi: 10.1137/06067016X.
- [51] The USC-SIPI Image Database. <http://sipi.usc.edu/database>. [Accessed: 2020.05.09.]

- [52] B. Ma, Y. Zhang, and S. Tian. Building reconstruction using three-dimensional zernike moments in digital surface model. In *IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium*, pages 1324–1327, 2018.