基于菲涅耳变换的不变矩提取及目标识别方法

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摘 要: 提出了一种基于菲涅耳变换的不变矩特征提取方法,并应用于图像目标识别.利用菲涅耳变换得到图像的衍射图样,将图像映射到菲涅耳衍射空间;在衍射空间提取几何矩或正交矩来获取图像全局信息的特征描述;利用 k 近邻法识别目标.实验结果表明基于菲涅耳变换的不变矩提取方法对于平移、尺度及旋转变化的图像目标具有更高的分类精度和抗噪声能力.

关 键 词: 不变矩; 菲涅耳变换; 特征提取; 目标识别

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Fresnel transform based invariant moments extraction and object recognition method

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Abstract: An invariant moments feature extraction method based on Fresnel transform was proposed, and applied to image recognition. The original image was mapped into the Fresnel diffraction projection space by using the Fresnel transform. The geometric or orthogonal moment invariants were extracted in the diffraction space, from which the characterization of the global image information can be obtained. The k-nearest neighbor classifier was employed to implement objects classification. Experimental results show that the proposed moment invariants extraction method achieves high recognition rates for different combinations of translation, scaling and rotation and is very robust to noise.

Key words: invariant moment; Fresnel transform; feature extraction; target recognition

不变矩在图像平移、伸缩、旋转时均保持不变,而且具有全局特性,因此成为目标识别的重要方法之一[1-5].目标识别常用的矩特征可分为几何矩[6]、复数矩和正交矩.几何矩和复数矩的核函数非正交,具有信息冗余,无法重构原图像.而正交矩如 Zernike 矩[7-8](ZM, Zernike Moment), Legendre 矩[9-10],伪 Zernike 矩[11](PZM, Pseudo-Zernike Moment), Tchebichef 矩[12-13]、正交 Fourier-Mellin 矩[14-15]等,是将图像投影在正交函数基上,因此可以重构原图像.另外,正交矩具有更好的噪声鲁棒性和图像描述能力[16-17].但是正交矩缺乏尺度变换不变性.

在物理光学研究领域,菲涅耳变换被用来描述光波的一种衍射现象——菲涅耳衍射模式[18].由于衍射模式能够展现物质结构丰富的细节信息,因此在材料科学和晶体学等领域中得到广泛应用[19-21].

本文基于菲涅耳变换,将图像变换到衍射模式空间,基于衍射模式,计算矩不变量然后构造目标的矩不变量特征,用于目标识别.

1 菲涅耳变换

1.1 菲涅耳变换的数学模型

光波的传播可以看作一个线性系统,基于菲

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涅耳-惠更斯原理可推导出[22]：

$$\boldsymbol{U}(x,y) = \iint_{-\infty}^{\infty} \boldsymbol{U}(x_0,y_0)\boldsymbol{h}(x-x_0,y-y_0)\,\mathrm{d}x_0\mathrm{d}y_0 \tag{1}$$

其中，$\boldsymbol{U}(x_0,y_0)$为孔径平面上的投射复振幅分布；$\boldsymbol{U}(x,y)$为观察平面上的复振幅分布输出函数；$\boldsymbol{h}(x-x_0,y-y_0)$为系统的脉冲响应. 当采用旁轴近似时，脉冲响应可近似为

$$\boldsymbol{h}(x-x_0,y-y_0) = \frac{1}{\mathrm{j}\lambda d}\exp(\mathrm{j}kz)\cdot \exp\left\{\mathrm{j}\frac{k}{2d}[(x-x_0)^2+(y-y_0)^2]\right\} \tag{2}$$

将式(2)代入式(1)可得直角坐标下的菲涅耳衍射的计算公式，即惠更斯-菲涅耳积分公式：

$$\boldsymbol{E}_\tau(x,y) = \frac{\exp(\mathrm{j}kd)}{\mathrm{j}\lambda d}\iint_{-\infty}^{+\infty}\boldsymbol{E}_0(x_0,y_0)\cdot \exp\left\{\frac{\mathrm{j}k}{2d}[(x-x_0)^2+(y-y_0)^2]\right\}\mathrm{d}x_0\mathrm{d}y_0 \tag{3}$$

其中，d 为传输距离；λ 为光波波长；k 为光波波数，且有 $k=\frac{2\pi}{\lambda}$. (x_0,y_0)和(x,y)分别为输入平面和输出平面坐标. 参数 τ 满足 $\tau^2=\lambda d$.

1.2 菲涅耳变换的幅值、实部及虚部

菲涅耳变换的幅值：

$$\boldsymbol{E}(x,y) = |\boldsymbol{E}_\tau(x,y)| \tag{4}$$

将式(3)中 $\boldsymbol{E}_\tau$ 的积分部分的指数项展开，则可得到 $\boldsymbol{E}_\tau$ 的实部和虚部，即菲涅耳变换的实部和虚部.

$$\boldsymbol{E}_\tau(x,y) = \boldsymbol{F}(x,y)+\mathrm{i}\boldsymbol{G}(x,y) \tag{5}$$

$$\boldsymbol{F}(x,y) = \frac{\exp(\mathrm{j}kd)}{\mathrm{j}\lambda d}\iint_{-\infty}^{+\infty}\boldsymbol{E}_0(x_0,y_0)\cdot \cos\left\{\frac{k}{2d}[(x-x_0)^2+(y-y_0)^2]\right\}\mathrm{d}x_0\mathrm{d}y_0 \tag{6}$$

$$\boldsymbol{G}(x,y) = \frac{\exp(\mathrm{j}kd)}{\mathrm{j}\lambda d}\iint_{-\infty}^{+\infty}\boldsymbol{E}_0(x_0,y_0)\cdot \sin\left\{\frac{k}{2d}[(x-x_0)^2+(y-y_0)^2]\right\}\mathrm{d}x_0\mathrm{d}y_0 \tag{7}$$

1.3 菲涅耳变换关于几何变换的性质

设 $f(x,y)$ 为图像的亮度灰度值，则根据公式，可得图像的菲涅耳变换为

$$\boldsymbol{E}_\tau(u,v) = \frac{\exp(\mathrm{j}kd)}{\mathrm{j}\lambda d}\iint_{-\infty}^{+\infty}f(x,y)\cdot \exp\left\{\frac{\mathrm{j}k}{2d}[(u-x)^2+(v-y)^2]\right\}\mathrm{d}x\mathrm{d}y \tag{8}$$

菲涅耳变换关于图像的几何变换的一些性质[23-24]如表 1 所示.

菲涅耳衍射图样在单纯的标度变换或距离变换下均无相似性，但在标度-距离同时变换下，菲涅耳衍射则可以具有相似性[25].

表 1 菲涅耳变换关于几何变换的性质

	原函数	菲涅耳变换后的函数
性质	$f(x,y)$	$\mathscr{E}_\tau(x,y)$
	$f(r,\theta)$	$\mathscr{E}_\tau(r,\theta)$
对偶性质	$(\mathscr{E}_\tau)^*(x,y)$	$f^*(x,y)$
平移性质	$f(x-x_0,y-y_0)$	$\mathscr{E}_\tau(x-x_0,y-y_0)$
尺度变换性质	$f\left(\frac{x}{s},\frac{y}{s}\right)$	$\mathscr{E}_{\frac{\tau}{s}}\left(\frac{x}{s},\frac{y}{s}\right)$
旋转变换性质	$f(r,\theta+\phi)$	$\mathscr{E}_\tau(r,\theta+\phi)$

1.4 基于菲涅耳变换的不变矩提取

设 $f(x,y)$ 为原始图像的亮度灰度值，本文以 Hu 矩(HM，Hu Moment)[16-17]为例说明基于菲涅耳变换的不变矩计算步骤：

步骤 1：基于菲涅耳变换，将原始图像映射到菲涅耳衍射空间，得到 $\boldsymbol{E}_\tau(x,y)$.

步骤 2：在菲涅耳衍射空间，计算菲涅耳变换的幅值函数 $E(x,y)$、实部 $F(x,y)$ 和虚部 $G(x,y)$.

步骤 3：利用幅值函数 $E(x,y)$、实部 $F(x,y)$ 和虚部 $G(x,y)$，计算低于三阶的 7 个 Hu 矩不变量 $\phi_1\sim\phi_7$，分别用 $E_1\sim E_7$，$F_1\sim F_7$，$G_1\sim G_7$ 表示.

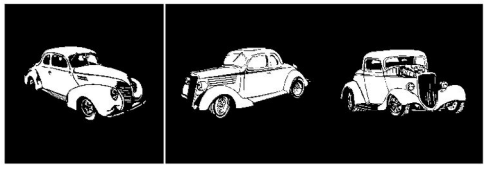
步骤 4：提取特征向量. 通常使用 $E_1\sim E_7$ 作为不变特征向量.

2 目标识别实验

在 PⅣ3.4GHz 2.5G RAM 微机上，使用 MatlabR2008a 语言编程实现目标识别实验. 实验数据 1 由简单的二值图像组成，如图 1 所示，图像分辨率均为 256×256.



a 图像集 A(飞机二值图)



b 图像集 B(汽车二值图)

图 1 飞机和汽车的标准图

实验数据 2[26]由形态复杂的灰度图像组成，如图 2 所示. 其中，图像集 C 中图像分辨率分别为：460×460，536×536，386×386，图像集 D 中图像分辨率分别为：372×372，394×394，460×

460.

目标实验由以下 3 个实验组成:

实验 1:测试不同方法在无噪声条件下分类精度;

实验 2:测试不同方法在不同程度高斯白噪声下的分类精度;

实验 3:测试不同方法在不同程度椒盐噪声下,对灰度图像的分类效果.



a　图像集 C(白鹭灰度图)



b　图像集 D(猫头鹰灰度图)

图 2　白鹭和猫头鹰的标准图

2.1　实验 1

将实验数据 1 中的图集 A 和 B 的每个图像在(−10,10)范围内随机平移,并按 $0.5<\lambda<1.5$ 的尺度因子 λ 随机进行尺度变换,再以 2°的增量旋转 0°~360°,构造对应图像集 A,B 的两组(每组 540(3×180)幅图像)测试集. 实验对比了在测试集图像空间计算 Hu 矩(HM, Hu Moment),Zernike 矩(ZM, Zernike Moment)和伪 Zernike 矩(PZM, Pesudo-Zernike Moment)与在菲涅耳衍射空间上计算上述 3 个不变矩 FHM(Fresnel Hu Moment),FZM(Fresnel Zernike Moment),FPZM(Fresnel Pesudo-Zernike Moment)的分类精度. 分类器为 k 近邻分类器.

采用正确分类率(CCPs, the Correct Classification Percentages)客观评估不变矩分类精度.

$$\text{正确分类率}=\frac{\text{正确分类的图像个数}}{\text{被识别的图像总数}}\times 100\% \tag{9}$$

分类结果如表 2 所示. 从表 2 可以看出,在无噪声的情况下,基于菲涅耳变换后计算矩不变量的正确分类率均高于原始图像空间计算矩不变量的正确分类率.

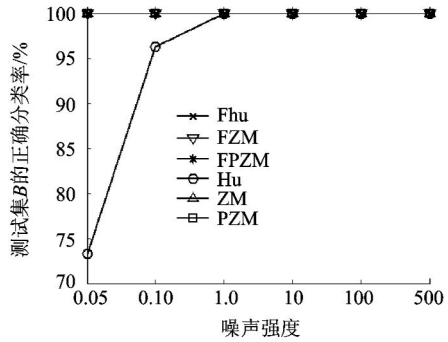
2.2　实验 2

将实验 1 生成的两个测试集 A,B 中的图像加入均值为 0,噪声强度分别为 0.05,0.1,1,10,100,500 的高斯白噪声,构造噪声测试图像集.

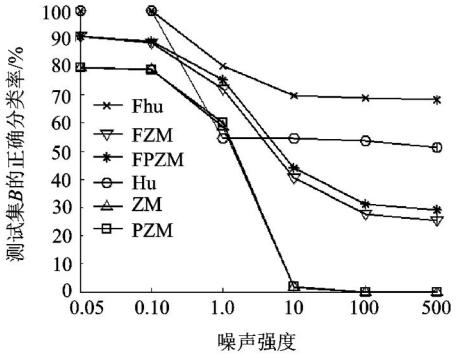
表 2　实验 1 分类结果

方法	数据集	正确分类率/%
HM	A	71.85
	B	100
FHM	A	100
	B	100
ZM	A	97.96
	B	87.96
FZM	A	100
	B	97.04
PZM	A	98.70
	B	88.15
FPZM	A	100
	B	97.59

采取和实验 1 相同的方法测试不变矩的分类精度. 分类结果的 CCPs 随噪声强度变化的曲线如图 3 所示. 由于测试集 A 的各种算法的正确分类率最后都保持在 100%,所以图 3a 的几条曲线在 100%处重合. 图 3b 的 CCPs 曲线显示,Zernike 矩和伪 Zernike 矩在噪声强度较大时无法正确分类图集 B,而基于菲涅耳衍射模式的 Zernike 矩、FZM、伪 Zernike 矩和 FPZM 能够得到较好的分类结果. 当噪声强度为 10 时,FZM 和 FPZM 对于图集 B 的正确分类率仍可以达到 40.56% 和 44.07%. 随着感染噪声的强度增大. 各种方法的正确分类率总体下降,但是由于噪声感染的随机性,下降过程中仍可能有上升的拐点.



a　测试集 A



b　测试集 B

图 3　不同方法在高斯白噪声条件下正确分类率的对比结果

2.3 实验 3

按照实验 1 构造测试数据的方法,基于实验数据 2,构造数据集 C,D 的测试图像. 然后在测试图像上分别叠加噪声强度为 0.001,0.01,0.1 的椒盐噪声. 由于 Zernike 矩、伪 Zernike 矩等正交矩只能对二值图像进行计算,首先使用大津阈值将图像转化成二值图像,然后再计算矩不变量. 分类结果如表 3 所示.

表 3 实验 2 的分类结果

噪声强度	数据集	正确分类率/%					
		HM	FHM	ZM	FZM	PZM	FPZM
0.0	C	83.7	77.04	80.74	99.81	81.11	100
	D	72.22	97.41	80.74	87.96	86.11	90.37
0.001	C	85.56	66.11	80.37	73.33	80.37	74.26
	D	70.74	88.15	80.19	86.11	85.37	87.22
0.01	C	83.52	92.59	94.44	80.74	94.63	81.11
	D	71.67	73.33	69.63	81.48	79.21	82.22
0.1	C	74.63	75.19	88.52	82.22	87.41	83.52
	D	83.15	76.67	82.04	84.26	67.41	85.56

表 3 实验结果表明,菲涅耳衍射模式下的不变矩对 D 组的分类结果基本都优于原始不变矩,但 FZM 和 FPZM 代表的正交矩对 C 组的分类结果较差. 这是因为正交矩本质上不具备平移与尺度不变特性. 采用大津阈值对灰度图进行二值化会造成重采样与重量化误差,另外加入的椒盐噪声也会对二值化造成影响. 因此对于灰度图,二值化过程会严重影响最后的结果,采用较好的二值化方法有可能会提高本文算法的性能.

3 结 论

本文提出了利用菲涅耳变换将图像变换到衍射空间模式,然后提取矩不变量的方法. 实验结果表明,在衍射空间计算图像矩不变量的分类精度优于在原始图像空间提取矩不变量的分类精度. 另外,衍射模式空间提取矩不变量的目标识别方法对噪声具有更好的鲁棒性.

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