Three-Directional Box-Splines: Characterization and Efficient Evaluation

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***Abstract*—We propose a new characterization of three-directional box-splines, which are well adapted for interpolation and approximation on hexagonal lattices. Inspired by a construction already applied with success for exponential splines [1] and hex-splines [2], we characterize a box-spline as a convolution of a generating function, which is a Green function of the spline's associated differential operator, and a discrete filter that plays the role of a localization operator. This process leads to an elegant analytical expression of three-directional box-splines. It also brings along a particularly efficient implementation.**

***Index Terms*—Approximation, box-splines, hexagonal sampling, interpolation, three-directional mesh.**

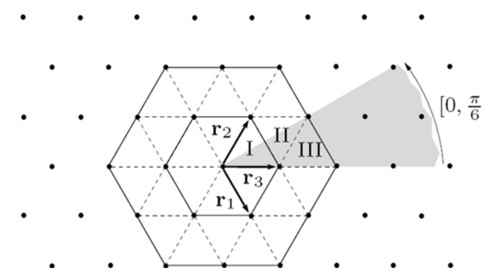

Fig. 1. Hexagonal lattice is generated using integer combinations of the vectors $\mathbf{r}_1$, $\mathbf{r}_2$, and $\mathbf{r}_3$. The hexagonal support of the first two box-splines $\chi^1(\mathbf{x})$ and $\chi^2(\mathbf{x})$ has been indicated. Box-splines are polynomial inside each triangle. Using the twelve-fold symmetry, χ^1 and χ^2 have only to be known in the triangles I, II, and III that intersect the sector $[0, \pi/6]$.

I. Introduction

The representation of a digital signal by means of a discrete/continuous model is essential for common tasks such as interpolation and resampling. For images and other two-dimensional (2-D) data, polynomial spline models based on B-splines are particularly popular, mainly due to their simplicity and excellent approximation capabilities [3].

For image data sampled on the traditional Cartesian lattice, separable B-splines can be obtained in a straightforward way using tensor products of one-dimensional (1-D) B-splines. However, in the case of sampling on a hexagonal lattice (aka three-directional mesh), separable B-splines are incapable of exploiting the highly praised isotropy and twelve-fold symmetry of this sampling scheme [4], [5]. *Box-splines* are a multidimensional extension of 1-D splines [6] that have found practical applications in geometric modeling, multiscale representation, and many other fields. Among the large box-spline family, three-directional (nonseparable) box-splines are particularly suitable for hexagonal lattices. They have been successfully applied in numerous problems where hexagonally sampled data are handled [7].

Early algorithms to evaluate box-spline surfaces were very memory consuming and only resulted into an approximation of the surface within a given tolerance [8], [9]. Later, more efficient methods were proposed based on the recursive properties of box-splines [10]–[12]. Here, we propose a new characterization of three-directional box-splines that provides us with a closed analytical formula, as well as an efficient implementation scheme. To this aim, we derive an explicit form of the generating function, which is the Green function of a three-directional differential operator associated with box-splines. Then, the box-spline can be expressed as the convolution of the generating function with a discrete filter, which plays the role of a localization operator. A similar construction was already applied on the Cartesian lattice to generalized polynomial splines (i.e., exponential splines and L-splines [1]) and to the design of hex-splines, another family of hexagonal splines [2].

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II. Box-Splines on the Hexagonal Lattice

A. Mathematical Preliminaries

A 2-D lattice is a set of points of the plane, characterized by two linearly independent vectors $\mathbf{v}_1$ and $\mathbf{v}_2$, grouped in a matrix $\mathbf{R} = [\mathbf{v}_1\ \mathbf{v}_2]$, such that the lattice sites are the locations $\mathbf{Rk}$ for every $\mathbf{k} \in \mathbb{Z}^{2\times 1}$. Within this letter, we define the vectors $\mathbf{e}_1 = [1\ 0]^{\mathrm{T}}$, $\mathbf{e}_2 = [0\ 1]^{\mathrm{T}}$, and those shown in Fig. 1 as

$$\mathbf{r}_1 = \begin{bmatrix} \frac{1}{2} \\ -\frac{\sqrt{3}}{2} \end{bmatrix}, \quad \mathbf{r}_2 = \begin{bmatrix} \frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{bmatrix}, \quad \mathbf{r}_3 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{1}$$

The Cartesian lattice is then obtained for $\mathbf{R} = [\mathbf{e}_1\ \mathbf{e}_2]$ and the regular hexagonal lattice, as in Fig. 1, for $\mathbf{R} = [\mathbf{r}_1\ \mathbf{r}_2]$.

Bivariate functions are equivalently denoted as $f(x_1, x_2)$, $x_1, x_2 \in \mathbb{R}$, or $f(\mathbf{x})$, where $\mathbf{x} = [x_1\ x_2]^{\mathrm{T}}$ is interpreted as a vector in $\mathbb{R}^2$. The Fourier transform of a function $f(\mathbf{x}) \in L_2(\mathbb{R}^2)$ is defined as $\hat{f}(\boldsymbol{\omega}) = \int_{\mathbb{R}^2} f(\mathbf{x}) \exp(-j\langle \boldsymbol{\omega}, \mathbf{x}\rangle) d\mathbf{x}$, where $\langle \boldsymbol{\omega}, \mathbf{x}\rangle = \boldsymbol{\omega}^{\mathrm{T}}\mathbf{x}$ is the usual inner product of vectors.

A 2-D discrete signal is denoted as $s[\mathbf{k}] = s[k_1, k_2]$, $k_1, k_2 \in \mathbb{Z}$. Its representation in the continuous domain, associated with the lattice sites $\mathbf{Rk}$, is a weighted Dirac comb: $s(\mathbf{x}) = \sum_{\mathbf{k}\in\mathbb{Z}^2} s[\mathbf{k}]\delta(\mathbf{x} - \mathbf{Rk})$. Consequently, its Fourier transform is defined accordingly as $\hat{s}(\boldsymbol{\omega}) = \sum_{\mathbf{k}\in\mathbb{Z}^2} s[\mathbf{k}] \exp(-j\langle \boldsymbol{\omega}, \mathbf{Rk}\rangle)$. For $\mathbf{z} = \exp(-j\mathbf{R}^{\mathrm{T}}\boldsymbol{\omega})$,

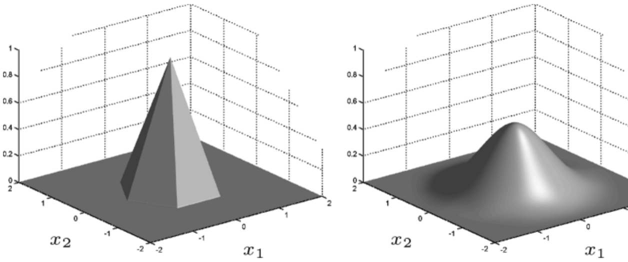

Fig. 2. First two box-splines (left) $\chi^1(\mathbf{x})$ and (right) $\chi^2(\mathbf{x})$.

we get the $\mathcal{Z}$-transform of s as $S(\mathbf{z}) = \sum_{\mathbf{k}\in\mathbb{Z}^2} s[\mathbf{k}]\mathbf{z}^{-\mathbf{k}}$ ($\mathbf{z}^{-\mathbf{k}}$ means $z_1^{-k_1} z_2^{-k_2}$). Convolutions are denoted by $*$.

B. Definition

A 2-D box-spline model defined on a lattice $\mathbf{R}$ has the form

$$f(\mathbf{x}) = \sum_{\mathbf{k}\in\mathbb{Z}^2} c[\mathbf{k}]\varphi_\Xi(\mathbf{x}-\mathbf{R}\mathbf{k}), \quad \mathbf{x}\in\mathbb{R}^2 \tag{2}$$

where $c[\mathbf{k}]$ are the box-spline coefficients that are weights for the box-spline basis functions $\varphi_\Xi(\mathbf{x})$, placed on every lattice site. They can be computed to ensure a desired property, typically that f interpolates a discrete available signal s (i.e., $f(\mathbf{R}\mathbf{k}) = s[\mathbf{k}]$ for every $\mathbf{k}$). The box-spline $\varphi_\Xi(\mathbf{x})$ depends on a concatenated matrix of N vectors $\Xi = [\mathbf{v}_1 \ \cdots \ \mathbf{v}_N]$ ($N \geq 2$) and can be defined as follows [6]. If $\Xi = [\mathbf{v}_1 \ \mathbf{v}_2]$, then

$$\varphi_{[\mathbf{v}_1 \ \mathbf{v}_2]}(\mathbf{x}) = \begin{cases} \frac{1}{|\det(\Xi)|}, & \text{if } \Xi^{-1}\mathbf{x}\in[0,1)^2 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

and inductively, $\varphi_{\Xi\cup[\mathbf{v}]}(\mathbf{x}) = \int_0^1 \varphi_\Xi(\mathbf{x}-t\mathbf{v})dt$.

Therefore, we have the normalization $\int_{\mathbb{R}^2}\varphi_\Xi = 1$ and the convolution property $\varphi_{\Xi_1\cup\Xi_2} = \varphi_{\Xi_1} * \varphi_{\Xi_2}$.

On a hexagonal lattice, box-splines can be constructed using the three vectors $\mathbf{r}_1$, $\mathbf{r}_2$, and $-\mathbf{r}_3$. In particular, we define the so-called Courant element [6] as $\chi^1 = (\sqrt{3}/2)\varphi_{[\mathbf{r}_1 \ \mathbf{r}_2 \ -\mathbf{r}_3]}$, where we have changed the normalization toward the density of the lattice, i.e., $|\det\mathbf{R}| = \sqrt{3}/2$. Further on, higher orders are obtained as $\chi^n = (2/\sqrt{3})\chi^{n-1} * \chi^1$, $n > 1$. Their expression in the Fourier domain is

$$\widehat{\chi}^n(\boldsymbol{\omega}) = \frac{\sqrt{3}}{2}\left(\frac{\exp(j\langle\boldsymbol{\omega},\mathbf{r}_3\rangle)\prod_{i=1}^3 1-\exp(-j\langle\boldsymbol{\omega},\mathbf{r}_i\rangle)}{(j\langle\boldsymbol{\omega},\mathbf{r}_1\rangle)(j\langle\boldsymbol{\omega},\mathbf{r}_2\rangle)(j\langle\boldsymbol{\omega},\mathbf{r}_3\rangle)}\right)^n \tag{4}$$

$$= \frac{\sqrt{3}}{2}\prod_{i=1}^3 \operatorname{sinc}\left(\frac{\langle\boldsymbol{\omega},\mathbf{r}_i\rangle}{2}\right)^n \tag{5}$$

where $\operatorname{sinc}(x) = \sin(x)/x$. The box-splines $\chi^n(\mathbf{x})$ have several attractive properties, such as a hexagonal compact support and twelve-fold symmetry, as illustrated in Figs. 1 and 2. In the next section, we provide closed analytical formulas for these box-splines in the spatial domain.

III. Differential Characterization of Box-Splines

A. B-Spline Refresher

In the 1-D case, a polynomial spline $f(x)$ for uniformly sampled data can be expressed similarly to (2) as $f(x) = \sum_{k\in\mathbb{Z}} c[k]\beta^n(x-k)$. β^n is the causal B-spline of degree $n\in\mathbb{N}$, which can be defined in the spatial domain as

$$\beta^n(x) = \Delta^{n+1} * \frac{(x)_+^n}{n!}. \tag{6}$$

We identify Δ^n as the nth iterate of the finite difference filter, which is usually expressed in the $\mathcal{Z}$-domain as $\Delta^n(z) = (1-z^{-1})^n$. Further on, we have the one-sided power function $(x)_+^n = \{x^n, \text{for } x > 0; 0, \text{ otherwise}\}$. The filtering process acts as a localization operator on the power function, i.e., β^n has a finite support. The term $(x)_+^n/n!$ is also called the generating function, and it corresponds to the (causal) Green function of the differential operator $\mathrm{L}^n = \mathrm{d}^n/\mathrm{d}x^n$, i.e., the function $\rho(x)$ such that $\mathrm{L}^n\{\rho\}(x) = \delta(x)$. This means that a polynomial spline of degree n, when differentiated $n+1$ times, is a weighted Dirac comb.

On the 2-D Cartesian lattice, we can easily use tensor-product B-splines: $\beta^n(\mathbf{x}) = \beta^n(x_1)\beta^n(x_2)$. Then, the associated differential operator is

$$\mathrm{L}^n = \frac{\partial^{2n}}{\partial x_1^n \partial x_2^n} = \mathrm{D}_{\mathbf{e}_1}^n \mathrm{D}_{\mathbf{e}_2}^n \xleftrightarrow{\mathcal{F}} (j\langle\boldsymbol{\omega},\mathbf{e}_1\rangle)^n (j\langle\boldsymbol{\omega},\mathbf{e}_2\rangle)^n \tag{7}$$

where $\mathrm{D}_\mathbf{v} f(\mathbf{x}) = \lim_{t\to 0}(f(\mathbf{x}+t\mathbf{v}) - f(\mathbf{x}))/t$. In that case, the (separable) generating function is $(\mathbf{x})_+^n/(n!)^2 = (x_1)_+^n(x_2)_+^n/(n!)^2$, and the corresponding localization operator $\Delta^n(\mathbf{z}) = \Delta^n(z_1)\Delta^n(z_2)$.

B. From Differential Operators to Generating Functions

Inspired by the B-spline construction using Green functions, we propose an extension for the box-splines on the hexagonal lattice. For this purpose, we introduce the three-directional differential operator $\mathrm{L}^n = (2/\sqrt{3})\mathrm{D}_{\mathbf{r}_1}^n \mathrm{D}_{\mathbf{r}_2}^n \mathrm{D}_{\mathbf{r}_3}^n$, $n \geq 1$. Its Fourier transform, in the sense of the distributions, is

$$\widehat{\mathrm{L}}^n(\boldsymbol{\omega}) = \frac{2}{\sqrt{3}}(j\langle\boldsymbol{\omega},\mathbf{r}_1\rangle)^n (j\langle\boldsymbol{\omega},\mathbf{r}_2\rangle)^n (j\langle\boldsymbol{\omega},\mathbf{r}_3\rangle)^n. \tag{8}$$

Proposition: A Green function $\rho^n(\mathbf{x})$ of the operator L^n, $n \geq 1$ is given by

$$\rho^n(\mathbf{x}) = \sum_{i=0}^{n-1}\binom{n-1+i}{i}\mu^{n-1-i,2n-1+i}(\mathbf{x}) \tag{9}$$

where

$$\mu^{n_1,n_2}(x_1,x_2) = \frac{1}{n_1! n_2!}\left(\frac{2|x_2|}{\sqrt{3}}\right)^{n_1}\left(x_1 - \frac{|x_2|}{\sqrt{3}}\right)_+^{n_2}. \tag{10}$$

The proof is given in the Appendix. Notice that the functions μ^{n_1,n_2} and ρ^n all have the same wedge-like support; they are causal in x_1 and symmetric in x_2, as illustrated in Fig. 3.

C. From Generating Functions to Box-Splines

In the Fourier domain, the generating function ρ^n corresponds to $\widehat{\chi}^n$ without its numerator in (4). The remaining term can be identified by introducing the discrete filter

$$\Delta(\mathbf{z}) = \left(1-z_1^{-1}\right)\left(1-z_2^{-1}\right)(z_1 z_2 - 1). \tag{11}$$

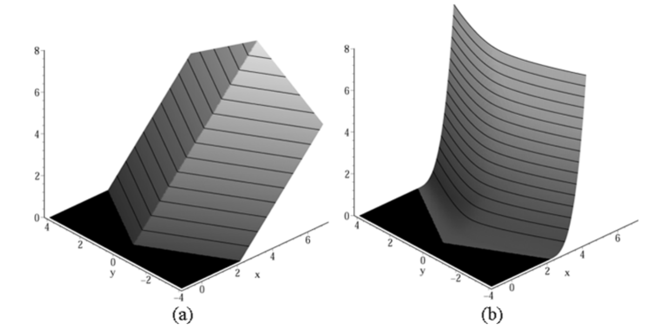

Fig. 3. Green functions (a) $\rho^1 = \mu^{0,1}$ and (b) $\rho^2 = \mu^{1,3} + 2\mu^{0,4}$, which serve to generate the box-splines χ^1 and χ^2.

Using the property $\mathbf{r}_3 = \mathbf{r}_1 + \mathbf{r}_2$, we find that $\widehat{\Delta}^n(\boldsymbol{\omega}) = \Delta(\exp(j\langle\boldsymbol{\omega},\mathbf{r}_1\rangle), \exp(j\langle\boldsymbol{\omega},\mathbf{r}_2\rangle))^n$ is exactly the numerator of (4). We can explicitly find the filter coefficients of Δ^n by expanding the nth power of the $\mathcal{Z}$-transform of (11). By collecting the coefficient in front of the term $z_1^{-k_1} z_2^{-k_2}$, we get for every $k_1, k_2 \in \mathbb{Z}$

$$\Delta^n[k_1,k_2] = \sum_{i=\max(k_1,k_2,0)}^{\min(n+k_1,n+k_2,n)} (-1)^{k_1+k_2+i} \times \binom{n}{i-k_1}\binom{n}{i-k_2}\binom{n}{i}. \quad (12)$$

By arranging the $\Delta^n[\mathbf{k}]$ at the lattice sites $\mathbf{Rk} = k_1\mathbf{r}_1 + k_2\mathbf{r}_2$, we can represent the first two localization filters as

$$\Delta = \begin{array}{ccccc} & -1 & & 1 & \\ 1 & & 0 & & -1 \\ & -1 & & 1 & \end{array}, \quad \Delta^2 = \begin{array}{ccccc} & 1 & -2 & 1 & \\ -2 & 2 & & 2 & -2 \\ 1 & 2 & -6 & 2 & 1 \\ -2 & 2 & & 2 & -2 \\ & 1 & -2 & 1 & \end{array}. \quad (13)$$

Putting together (11) and (8) with the fact that $\widehat{\mathrm{L}}^n(\boldsymbol{\omega})\widehat{\rho}^n(\boldsymbol{\omega}) = 1$, we find that $\widehat{\chi}^n(\boldsymbol{\omega}) = \widehat{\Delta}^n(\boldsymbol{\omega})\widehat{\rho}^n(\boldsymbol{\omega})$. Therefore, we obtain the characterization

$$\chi^n(\mathbf{x}) = \Delta^n * \rho^n(\mathbf{x}) = \sum_{\mathbf{k}\in\mathbf{Z}^2} \Delta^n[\mathbf{k}]\rho^n(\mathbf{x}-\mathbf{Rk}). \quad (14)$$

The complete analytical expression of $\chi^n(\mathbf{x})$, $n \geq 1$ can then be written as $\chi^n(x_1,x_2) =$

$$\sum_{k_1,k_2=-n}^{n} \sum_{i=\max(k_1,k_2,0)}^{\min(n+k_1,n+k_2,n)} (-1)^{k_1+k_2+i}\binom{n}{i-k_1}\binom{n}{i-k_2}\binom{n}{i} \times \sum_{d=0}^{n-1}\binom{n-1+d}{d}\frac{1}{(2n-1+d)!(n-1-d)!} \times \left|\frac{2x_2}{\sqrt{3}} + k_1 - k_2\right|^{n-1-d} \times \left(x_1 - \frac{k_1+k_2}{2} - \left|\frac{x_2}{\sqrt{3}} + \frac{k_1-k_2}{2}\right|\right)_+^{2n-1+d}. \quad (15)$$

IV. Implementation Issues

A. Generic Case

Equation (15) provides us with an efficient way to evaluate at any point $\mathbf{x}$, any three-directional box-spline χ^n. Notice that the power functions grow rapidly, as shown in Fig. 3, which could lead to problems of numerical stability. A simple remedy consists of evaluating χ^n only for $x_1 \leq 0$, which exploits the causality of ρ^n in x_1 and the symmetry $\chi^n(x_1,x_2) = \chi^n(-x_1,x_2)$. The following Matlab code performs box-spline evaluations for a list of points $(\mathtt{x[m]}, \mathtt{y[m]})$, indexed by m. The twelve-fold symmetry is used to fold coordinates into the sector $[5\pi/6, \pi]$, where the number of evaluations of the power functions is minimal. We use the coordinates (u,v) in the basis $(\mathbf{r}_1,\mathbf{r}_2)$, instead of the coordinates (x,y) in the canonical basis $(\mathbf{e}_1,\mathbf{e}_2)$. nchoosek(n, k) gives the binomial coefficient (n,k).

```
function val=boxspline(x,y,n)
x=-abs(x);  y=abs(y);
u=x-y/sqrt(3);  v=x+y/sqrt(3);
id=find(v>0);   v(id)=-v(id);  u(id)=u(id)+v(id);
id=find(v>u/2); v(id)=u(id)-v(id);
val=zeros(size(x));
for K=-n:ceil(max(max(u)))-1,
  for L=-n:ceil(max(max(v)))-1,
    for i=0:min(n+K,n+L),
      coeff=(-1)^(K+L+i)*nchoosek(n,i-K)*...
        nchoosek(n,i-L)*nchoosek(n,i);
      for d=0:n-1,
        aux=abs(v-L-u+K);
        aux2=(u-K+v-L-aux)/2;
        aux2(find(aux2<0))=0;
        val=val+coeff*nchoosek(n-1+d,d)/...
          factorial(2*n-1+d)/factorial(n-1-d)*...
          aux.^(n-1-d).*aux2.^(2*n-1+d);
end, end, end, end
```

This code was used to generate the plots in Fig. 2. The computational complexity is polynomial in n, compared to exponential for recursive methods in the literature [10]–[12]. For example, the evaluation boxspline(1, 1, 3) took 0.002 s, while 47 s were required for the same operation using the Matlab code proposed in [11] (that can evaluate any box-spline, not just the three-directional ones).

B. Further Optimization for Fixed n

For evaluating a box-spline χ^n of fixed n, an attractive hybrid analytical/numerical implementation consists in determining the polynomial form $p(\mathbf{x})$ inside each triangle of the three-directional mesh. This polynomial, which is obtained by the sums of (15), can be precomputed, stored, and only evaluated at the end. The following code in C-language for χ^2 may serve as a template: coordinates are first folded in the sector $[0, \pi/2]$, then in $[0, \pi/3]$, and finally in $[0, \pi/6]$. This is done conveniently with the coordinates (u,v). The coordinates $(g = u - v/2, v)$ in the orthogonal basis $(\mathbf{r}_1, (\mathbf{r}_2+\mathbf{r}_3)/2)$ are the most appropriate for having short polynomials with rational coefficients in each triangle.

```
float boxspline2(float x, float y) {
  float u=fabs(x)-fabs(y)/sqrt(3.0);
  float v=fabs(x)+fabs(y)/sqrt(3.0);
  if (u<0)   { u=-u; v=v+u; }       /*symmetry % r2*/
  if (2*u<v) u=v-u;               /*symmetry % r2+r3*/
  float g=u-v/2.0;
  if (v>2.0) return 0.0;      /*outside the support*/
  if (v<1.0) return 0.5+((5/3.0-v/8.0)*v-3)*v*v/4.0+
    ((1-v/4.0)*v+g*g/6.0-1)*g*g;      /*triangle I*/
  if (u>1.0) return (v-2)*(v-2)*(v-2)*(g-1)/6.0;
  return 5/6.0+((1+(1/3.0-v/8.0)*v)*v/4.0-1)*v+
    ((1-v/4.0)*v+g*g/6.0-1)*g*g;     /*triangle II*/
}
```

V. Conclusion

We proposed a new characterization of the three-directional box-splines, based on a Green function of the differential operator adapted to the hexagonal lattice. Together with a finite difference filter that acts as a localization operator on the generating function, this provides us with new explicit analytical formulas for the three-directional box-splines. This characterization also leads to particularly easy and efficient implementations. We provided the Matlab source code for the generic case and a further optimized C-code for the case $n = 2$. The latter one could be particularly interesting for high-quality visualization of data sampled on a hexagonal lattice.

Finally, we note that these box-splines can be expressed on any lattice with matrix $\mathbf{R}'$, and not only on the hexagonal one, by the simple change of basis $\chi^n(\mathbf{R}\mathbf{R}'^{-1}\mathbf{x})$.

Appendix
Proof of the Proposition

We verify whether ρ^n of (9) is a Green function of L^n, i.e., we need $\mathrm{L}^n\{\rho^n\}(\mathbf{x}) = \delta(\mathbf{x})$. First, we introduce the vectors

$$\mathbf{r}_1^\perp = \begin{bmatrix} 1 \\ \frac{1}{\sqrt{3}} \end{bmatrix}, \quad \mathbf{r}_2^\perp = \begin{bmatrix} 1 \\ -\frac{1}{\sqrt{3}} \end{bmatrix}, \quad \mathbf{r}_3^\perp = \begin{bmatrix} 0 \\ \frac{2}{\sqrt{3}} \end{bmatrix} \tag{16}$$

which allow us to express the dual bases of $(\mathbf{r}_2, \mathbf{r}_3)$ and $(\mathbf{r}_1, \mathbf{r}_3)$ as $(\mathbf{r}_3^\perp, \mathbf{r}_2^\perp)$ and $(-\mathbf{r}_3^\perp, \mathbf{r}_1^\perp)$, respectively. For example, the coordinates of $\mathbf{x}$ in $(\mathbf{r}_2, \mathbf{r}_3)$ are $(\langle \mathbf{x}, \mathbf{r}_3^\perp\rangle, \langle \mathbf{x}, \mathbf{r}_2^\perp\rangle)$.

We now derive the Fourier expression of μ^{n_1,n_2}, which we first rewrite as

$$\begin{aligned} \mu^{n_1,n_2}(x_1,x_2) &= (x_2)_+^0 \mu^{n_1,n_2}(x_1,x_2) \\ &\quad + (-x_2)_+^0 \mu^{n_1,n_2}(x_1,x_2) \\ &= \left(\langle \mathbf{x}, \mathbf{r}_3^\perp\rangle\right)_+^{n_1} \left(\langle \mathbf{x}, \mathbf{r}_2^\perp\rangle\right)_+^{n_2} \\ &\quad + \left(\langle \mathbf{x}, -\mathbf{r}_3^\perp\rangle\right)_+^{n_1} \left(\langle \mathbf{x}, \mathbf{r}_1^\perp\rangle\right)_+^{n_2}. \end{aligned} \tag{17}$$

From distribution theory, we know the Fourier transform of the one-sided power function

$$(x)_+^n \stackrel{\mathcal{F}}{\longleftrightarrow} \frac{n!}{(j\omega)^{n+1}} + \mathcal{D}(\boldsymbol{\omega}) \tag{18}$$

where $\mathcal{D}$ is essentially the nth derivative of Dirac. This term can be omitted since it does not have any influence when applying a differential operator of order n (continuous or discrete) to $(x)_+^n$ (see also [2, App. C]).

Hence, using a tensor product and a change of basis from $(\mathbf{e}_1, \mathbf{e}_2)$ to $(\mathbf{r}_2, \mathbf{r}_3)$ (with Jacobian $|\det[\mathbf{r}_2\mathbf{r}_3]| = \sqrt{3}/2$), we get

$$(x_2)_+^0 \mu^{n_1,n_2} \stackrel{\mathcal{F}}{\longleftrightarrow} \frac{\sqrt{3}/2}{\left(j\langle \boldsymbol{\omega}, \mathbf{r}_2\rangle\right)^{n_1+1} \left(j\langle \boldsymbol{\omega}, \mathbf{r}_3\rangle\right)^{n_2+1}}. \tag{19}$$

Similarly, the Fourier transform of $(-x_2)_+^0 \mu^{n_1,n_2}$ is obtained by replacing $\mathbf{r}_2$ by $\mathbf{r}_1$ in (19).

We now define the functions γ^{n_1,n_2,n_3}, for any integers n_1, n_2, and n_3 as

$$\gamma^{n_1,n_2,n_3} \stackrel{\mathcal{F}}{\longleftrightarrow} \frac{\frac{\sqrt{3}}{2}}{\left(j\langle \boldsymbol{\omega}, \mathbf{r}_1\rangle\right)^{n_1} \left(j\langle \boldsymbol{\omega}, \mathbf{r}_2\rangle\right)^{n_2} \left(j\langle \boldsymbol{\omega}, \mathbf{r}_3\rangle\right)^{n_3}}. \tag{20}$$

We recognize $\rho^n = \gamma^{n,n,n}$, $n \geq 1$. Using the property $\mathbf{r}_3 = \mathbf{r}_1 + \mathbf{r}_2$, we can further obtain the following recurrence relation, for $n_1 \geq 1, n_2 \geq 1, n_3 \geq 0$:

$$\gamma^{n_1,n_2,n_3} = \gamma^{n_1-1,n_2,n_3+1} + \gamma^{n_1,n_2-1,n_3+1}. \tag{21}$$

By recurrence on $n_1 + n_2$, we can also show that

$$\begin{aligned} \gamma^{n_1,n_2,n_3} &= \sum_{i=0}^{n_1-1} \binom{n_2-1+i}{i} \gamma^{n_1-i,0,n_2+n_3+i} \\ &\quad + \sum_{i=0}^{n_2-1} \binom{n_1-1+i}{i} \gamma^{0,n_2-i,n_1+n_3+i}. \end{aligned} \tag{22}$$

In the case of ρ^n, we have

$$\rho^n = \sum_{i=0}^{n-1} \binom{n-1+i}{i} \left(\gamma^{n-i,0,2n+i} + \gamma^{0,n-i,2n+i}\right). \tag{23}$$

Finally, we identify the function μ^{n_1,n_2} as

$$\mu^{n_1,n_2} = \gamma^{0,n_1+1,n_2+1} + \gamma^{n_1+1,0,n_2+1} \tag{24}$$

which results in (9).

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