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APPROXIMATE APPROXIMATIONS ON NONUNIFORM GRIDS

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We present an extension of approximate quasi-interpolation on uniformly distributed nodes, to functions given on a set of nodes close to an uniform, not necessarily cubic, grid.

1. Introduction

The method of approximate quasi-interpolation and its first related results were proposed in [5] and [14]. The method is characterized by a very accurate approximation in a certain range relevant for numerical computations, but in general the approximations do not converge in rigorous sense. For that reason such processes were called *approximate approximations*.

Suppose we want to approximate a smooth function $u(\mathbf{x})$, $\mathbf{x} \in \mathbb{R}^n$, when we prescribe the values of u at the points of an uniform grid of mesh size h. We fix a positive parameter $\mathscr{D}$ and we choose a sufficiently smooth and rapidly decaying at infinity function η - the generating function - such that the linear combination of dilated shifts of η forms an approximate partition of the unity *i.e.*

$$\mathscr{D}^{-n/2} \sum_{\mathbf{m} \in \mathbb{Z}^n} \eta\left(\frac{\xi - \mathbf{m}}{\sqrt{\mathscr{D}}}\right) \approx 1.$$

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The method consists in approximating the function u at the point $\mathbf{x}$ by a linear combination of the form

$$M_{h,\mathscr{D}}u(\mathbf{x}) = \mathscr{D}^{-n/2} \sum_{\mathbf{m}\in\mathbb{Z}^n} u(h\mathbf{m})\eta\left(\frac{\mathbf{x}-h\mathbf{m}}{h\sqrt{\mathscr{D}}}\right), \qquad \mathbf{x}\in\mathbb{R}^n. \tag{1}$$

This type of formulas is known as quasi-interpolants and they have the property that $M_{h,\mathscr{D}}u(\mathbf{x})$ approximates $u(\mathbf{x})$, but $M_{h,\mathscr{D}}u(\mathbf{x})$ does not converge to $u(\mathbf{x})$ as the grid size h tends to zero. However one can fix $\mathscr{D}$ such that the approximation error is as small as we wish so that the non-convergence is not perceptible in numerical computations (see [7], [9]). On the other hand, the simplicity of the generalizations to the multi-dimensional case together with a great flexibility in choosing the generating function η compensate the lack of convergence.

The above mentioned flexibility is important in the applications because the generating function η can be selected so that integral and pseudo-differential operators of mathematical physics applied to η have analitically known expressions, obtaining semianalytic cubature formulas for these operators (see [6], [8], [11] and the review paper [13]). In some cases, *e.g.* for potentials, the cubature formulas converge even in a rigorous sense.

Another important application of the method is the possibility to develop explicit semi-analytic time marching algorithms for initial boundary value problems for linear and non linear evolution equations (see [12], [2]).

Quasi-interpolation formulas similar to (1) preserve the fundamental properties of approximate quasi-interpolation if the grid is a smooth image of the uniform one (see [10]) or if the grid is piecewise uniform (see [1]). The method of approximate quasi-interpolation has been generalized to functions given on a set of nodes close to a uniform, not necessary cubic, grid in [4]. More general scattered grids have been considered in [3].

To illustrate the unusual behavior of approximate approximations we assume $\eta(x) = \mathrm{e}^{-x^2}/\sqrt{\pi}$ as generating function and the following quasi-interpolant for a function u on $\mathbb{R}$:

$$M_{h,\mathscr{D}}u(x) = \frac{1}{\sqrt{\pi D}} \sum_{m=-\infty}^{\infty} u(hm)\mathrm{e}^{-(x-hm)^2/(\mathscr{D}h^2)}, \quad x\in\mathbb{R}. \tag{2}$$

The application of Poisson's summation formula to the function

$$\Theta(\xi,\mathscr{D}) = \frac{1}{\sqrt{\pi\mathscr{D}}} \sum_{m=-\infty}^{\infty} \mathrm{e}^{-(\xi-m)^2/\mathscr{D}}$$

yields to these equivalent representations for

$$\Theta(\xi,\mathscr{D}) = 1 + 2\sum_{\nu=1}^{\infty} \mathrm{e}^{-\pi^2\mathscr{D}\nu^2}\cos 2\pi\nu\xi$$

and

$$\Theta'(\xi,\mathscr{D}) = -4\pi\sum_{\nu=1}^{\infty}\nu e^{-\pi^2\mathscr{D}\nu^2}\sin 2\pi\nu\xi.$$

We deduce that

$$|\Theta(\xi,\mathscr{D})-1| \le 2\sum_{\nu=1}^{\infty} e^{-\pi^2\mathscr{D}\nu^2} < 2\,\varepsilon(\mathscr{D});$$

$$|\Theta'(\xi,\mathscr{D})| \le 4\pi\sum_{\nu=1}^{\infty}\nu e^{-\pi^2\mathscr{D}\nu^2} < 4\,\pi\,\varepsilon(\mathscr{D})$$

with

$$\varepsilon(D) = e^{-\pi^2\mathscr{D}} + \mathscr{O}(e^{-4\pi^2\mathscr{D}}).$$

The rapid exponential decay ensures that we can choose $\mathscr{D}$ large enough such that $\varepsilon(\mathscr{D})$ can be made arbitrarily small, for example less that the needed accuracy or the machine precision. Therefore the integer shifts of the Gaussian $\{\frac{e^{-(\xi-m)^2/\mathscr{D}}}{\sqrt{\pi\mathscr{D}}}, m\in\mathbb{Z}\}$ form an approximate partition of unity for large $\mathscr{D}$.

If the approximated function u is smooth enough, the quasi-interpolant (2) can be represented in the form (see [14])

$$M_{h,\mathscr{D}}u(x) = u(x)+$$

$$u(x)\left(\Theta(\frac{x}{h},\mathscr{D})-1\right) + u'(x)\frac{h\mathscr{D}}{2}\Theta'(\frac{x}{h},\mathscr{D}) + \mathscr{R}_{h,\mathscr{D}}(x)$$

where the remainder term admits the estimate

$$|\mathscr{R}_{h,\mathscr{D}}(x)| \le c\,\mathscr{D}h^2\max_{x\in\mathbb{R}}|u''(x)|$$

with a contant c not depending on $h,\mathscr{D},u$.

The difference between $M_{h,\mathscr{D}}u(x)$ and $u(x)$ can be estimated by

$$|M_{h,\mathscr{D}}u(x)-u(x)| \le c\mathscr{D}h^2\max_{x\in\mathbb{R}}|u''(x)|+$$

$$\varepsilon(\mathscr{D})(2|u(x)|+\frac{h\mathscr{D}}{2}|u'(x)|). \qquad (3)$$

This means that, above the tolerance (3), the quasi-interpolant (2) approximates u like usual second order approximations and, if $\mathscr{D}$ is chosen appropriately, any prescribed accuracy can be reached. Then the non-convergent part - called *saturation error* because it does not converge to 0 - can be neglected and the approximation process behaves like a second order approximation process.

2. Quasi-interpolation on uniform grids

One of the advantages of the method is that quasi-interpolants in arbitrary space dimension n with approximation order larger than two, up to some prescribed accuracy, have the same simple form as second order quasi-interpolants. The quasi-interpolant in $\mathbb{R}^n$ has the form

$$M_{h,\mathscr{D}}u(\mathbf{x}) = \mathscr{D}^{-n/2} \sum_{\mathbf{j}\in\mathbb{Z}^n} u(h\mathbf{j})\; \eta\left(\frac{\mathbf{x}-h\mathbf{j}}{h\sqrt{\mathscr{D}}}\right) \tag{4}$$

with the generating function η in the Schwartz space $\mathscr{S}(\mathbb{R}^n)$ of smooth and rapidly decaying functions. Maz'ya and Schmidt have proved that formula (4) provides the following approximation result.

Theorem 2.1. ([10]) *Suppose that*

$$\int_{\mathbb{R}^n} \eta(\mathbf{y})d\mathbf{y} = 1, \; \int_{\mathbb{R}^n} \mathbf{y}^\alpha \eta(\mathbf{y})d\mathbf{y} = 0, \forall \alpha : 1 \le |\alpha| < N \tag{5}$$

and $u \in W_\infty^N(\mathbb{R}^n)$. *Then*

$$|M_{h,\mathscr{D}}u(\mathbf{x}) - u(\mathbf{x})| \le c_{\eta,N}(\sqrt{\mathscr{D}}h)^N \|\nabla_N u\|_{L_\infty} +$$

$$\sum_{k=0}^{N-1} \left(\frac{h\sqrt{\mathscr{D}}}{2\pi}\right)^k \sum_{|\alpha|=k} \frac{|\nabla_k u(\mathbf{x})|}{\alpha!} \sum_{\nu\in\mathbb{Z}^n\setminus 0} |\partial^\alpha \mathscr{F}\eta(\sqrt{\mathscr{D}}\nu)|$$

with the constant $c_{\eta,N}$ *not depending on u, h and* $\mathscr{D}$.

Moreover for any $\varepsilon > 0$, *there exists* $\mathscr{D} > 0$ *such that for all* α, $0 \le |\alpha| < N$,

$$\sum_{\nu\in\mathbb{Z}^n\setminus 0} |\partial^\alpha \mathscr{F}\eta(\sqrt{\mathscr{D}}\nu)| < \varepsilon\,.$$

$\nabla_k u(x)$ denotes the vector of all partial derivatives $\{\partial^\alpha u(x)\}_{|\alpha|=k}$ and $\mathscr{F}\eta$ denotes the Fourier transform of η. We deduce that for any $\varepsilon > 0$ there exists $\mathscr{D} > 0$ such that $M_{h,\mathscr{D}}u(\mathbf{x})$ approximates $u(\mathbf{x})$ pointwise with the estimate (see [7],[9])

$$|M_{h,\mathscr{D}}u(\mathbf{x}) - u(\mathbf{x})| \le c_{\eta,N}(\sqrt{\mathscr{D}}h)^N \|\nabla_N u\|_{L_\infty} + \varepsilon \sum_{k=0}^{N-1} (h\sqrt{\mathscr{D}})^k |\nabla_k u(\mathbf{x})|.$$

Therefore $M_{h,\mathscr{D}}u$ behaves like an approximation formula of order N up to the saturation term that can be ignored in numerical computations if $\mathscr{D}$ is large enough. Similar estimates are also valid for integral norms (see [6]).

Several methods to construct generating functions satisfying the moment conditions (5) for arbitrarily large N have been developed (see [9], [10]). In fact any sufficiently smooth and rapidly decaying function η with $\mathscr{F}\eta(0) \ne 0$ can be used to construct new generating functions η_N satisfying the moment conditions for arbitrary large N as shown in the next theorem.

Theorem 2.2. ([9]) *Let* $\eta \in \mathscr{S}(\mathbb{R}^n)$ *with* $\mathscr{F}\eta(0) \neq 0$. *Then*

$$\eta_N(\mathbf{x}) = \sum_{|\alpha|=0}^{N-1} \frac{\partial^\alpha (\mathscr{F}\eta(\lambda)^{-1})|_{\lambda=0}}{\alpha!(2\pi i)^{|\alpha|}} \partial^\alpha \eta(\mathbf{x})$$

satisfies the moment conditions (5).

An interesting example is given by the Gaussian function $\eta(\mathbf{x}) = \mathrm{e}^{-|\mathbf{x}|^2}$ where the application of Theorem 2.2 leads to the generating function

$$\eta_{2M}(\mathbf{x}) = \pi^{-n/2} \sum_{j=0}^{M-1} \frac{(-1)^j}{j!4^j} \Delta^j \mathrm{e}^{-|\mathbf{x}|^2} = \pi^{-n/2} L_{M-1}^{(n/2)}(|\mathbf{x}|^2)\mathrm{e}^{-|\mathbf{x}|^2}$$

with $N = 2M$ and the generalized Laguerre polynomial

$$L_k^{(\gamma)}(y) = \frac{\mathrm{e}^y y^{-\gamma}}{k!} \left(\frac{d}{dy}\right)^k (\mathrm{e}^{-y} y^{k+\gamma}),\ \gamma > -1\,.$$

Hence the quasi-interpolant

$$M_{h,\mathscr{D}} u(\mathbf{x}) = (\pi \mathscr{D})^{-n/2} \sum_{\mathbf{j}\in\mathbb{Z}^n} u(h\mathbf{j})\, L_{M-1}^{(n/2)}\Big(\left|\frac{\mathbf{x}-h\mathbf{j}}{h\sqrt{\mathscr{D}}}\right|^2\Big)\mathrm{e}^{-\left|\frac{\mathbf{x}-h\mathbf{j}}{h\sqrt{\mathscr{D}}}\right|^2}$$

is an approximation formula of order $N = 2M$ plus the saturation term.

The quasi-interpolation formula and the corresponding approximation results have been generalized in [1] and [4] to the case when the values of u are given on uniform grids, not necessarily cubic, of this type

$$\Lambda_h := \{hA\mathbf{j}\,,\ \mathbf{j} \in \mathbb{Z}^n\}$$

with a real nonsingular $n\times n$-matrix A.

Under the same assumptions on the generating function η, it is always possible to choose $\mathscr{D} > 0$ such that the quasi-interpolant

$$\mathscr{M}_{\Lambda_h} u(\mathbf{x}) := \frac{\det A}{\mathscr{D}^{n/2}} \sum_{\mathbf{j}\in\mathbb{Z}^n} u(hA\mathbf{j})\, \eta\Big(\frac{\mathbf{x}-hA\mathbf{j}}{\sqrt{\mathscr{D}}h}\Big) \tag{6}$$

satisfies an estimate similar to that obtained in Theorem 2.1 for uniform cubic grid *i.e.*

$$|\mathscr{M}_{\Lambda_h} u(\mathbf{x}) - u(\mathbf{x})| \leq c_{\eta,N}(\sqrt{\mathscr{D}}h)^N \|\nabla_N u\|_{L_\infty} + \varepsilon \sum_{k=0}^{N-1} (h\sqrt{\mathscr{D}})^k |\nabla_k u(\mathbf{x})| \tag{7}$$

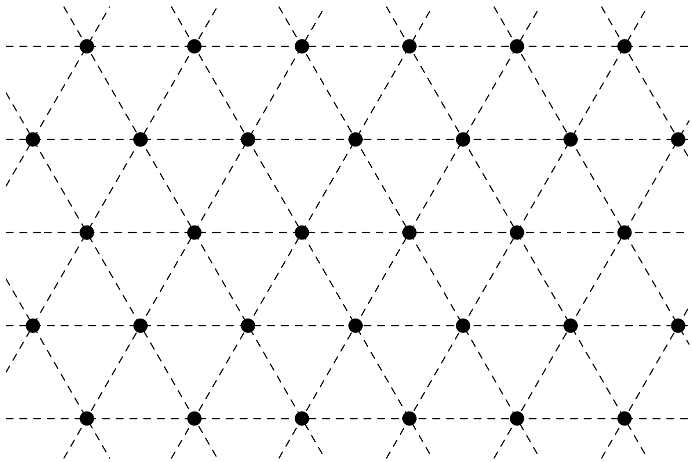

Figure 1: Tridiagonal grid

for any $\varepsilon > 0$.

The first application of formula (6) is the construction of quasi-interpolants on a regular triangular grid in the plane, as indicated in Figure 1.

The vertices $\mathbf{y}_{\mathbf{j}}^{\triangle}$ of a partition of the plane into equilateral triangles of side length 1 are given by

$$\mathbf{y}_{\mathbf{j}}^{\triangle} = A\mathbf{j}; \qquad A = \begin{pmatrix} 1 & 1/2 \\ 0 & \sqrt{3}/2 \end{pmatrix}.$$

The application of formula (6) to the nodes of the regular triangular grid of size h

$$\Lambda_h = \{h\mathbf{y}_{\mathbf{j}}^{\triangle}\} = \{hA\mathbf{j}\}_{\mathbf{j}\in\mathbb{Z}^2}$$

gives the following quasi-interpolant

$$\mathscr{M}_h^{\triangle} u(\mathbf{x}) := \frac{\sqrt{3}}{2\mathscr{D}} \sum_{\mathbf{j}\in\mathbb{Z}^2} u(h\mathbf{y}_{\mathbf{j}}^{\triangle})\, \eta\Big(\frac{\mathbf{x}-h\mathbf{y}_{\mathbf{j}}^{\triangle}}{\sqrt{\mathscr{D}}h}\Big).$$

The system of functions $\{\frac{\sqrt{3}}{2\mathscr{D}}\eta\Big(\frac{\mathbf{x}-\mathbf{y}_{\mathbf{j}}^{\triangle}}{\sqrt{\mathscr{D}}}\Big)\}$, centered at the points of the uniform triangular grid, forms an approximate partition of unity. Using Poisson's summation formula one can bound the main term of the saturation error by

$$\Big|1 - \frac{\sqrt{3}}{2\mathscr{D}} \sum_{\mathbf{j}\in\mathbb{Z}^2} \eta\Big(\frac{\mathbf{x}-\mathbf{y}_{\mathbf{j}}^{\triangle}}{\sqrt{\mathscr{D}}}\Big)\Big| \le \sum_{\nu\in\mathbb{Z}^2\setminus 0} \Big|\int_{\mathbb{R}^2} \eta(\mathbf{y})\, \mathrm{e}^{-2\pi \mathrm{i}\sqrt{\mathscr{D}}(\mathrm{A}^{-1}\mathbf{y},\nu)} \mathbf{dy}\Big|.$$

By assuming as generating function the Gaussian $\eta(\mathbf{x}) = \pi^{-1}\mathrm{e}^{-|\mathbf{x}|^2}$ we obtain

$$\Big|1-\frac{\sqrt{3}}{2\pi\mathscr{D}}\sum_{\mathbf{j}\in\mathbb{Z}^2}\mathrm{e}^{-|\mathbf{x}-\mathbf{y}_\mathbf{j}^\triangle|^2/\mathscr{D}}\Big| \le \sum_{(\nu_1,\nu_2)\neq(0,0)}\mathrm{e}^{-4\pi^2\mathscr{D}(\nu_1^2-\nu_1\nu_2+\nu_2^2)/3} = 6\,\mathrm{e}^{-4\pi^2\mathscr{D}/3}+\mathscr{O}(\mathrm{e}^{-4\pi^2\mathscr{D}}).$$

In Figure 2 the graph of the difference $\frac{\sqrt{3}}{2\pi\mathscr{D}}\sum_{\mathbf{j}\in\mathbb{Z}^2}\mathrm{e}^{-|\mathbf{x}-\mathbf{y}_\mathbf{j}^\triangle|^2/\mathscr{D}}-1$ is plotted with two different values of D.

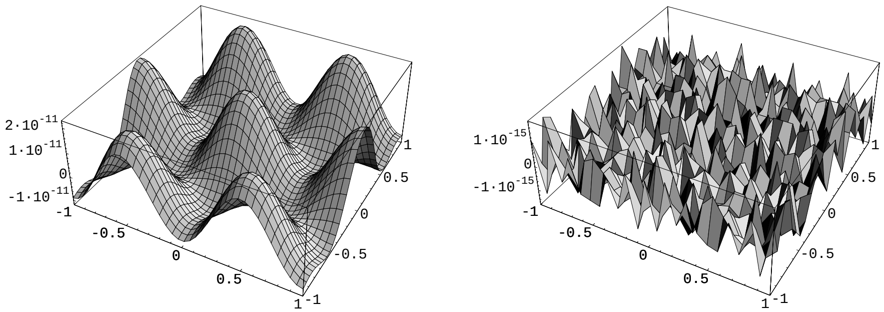

Figure 2: The graph of $\frac{\sqrt{3}}{2\pi\mathscr{D}}\sum_{\mathbf{j}\in\mathbb{Z}^2}\mathrm{e}^{-|\mathbf{x}-\mathbf{y}_\mathbf{j}^\triangle|^2/\mathscr{D}}-1$ when $D=2$ (on the left) and $D=3$ (on the right).

As second example we construct quasi-interpolants with functions centered at the nodes of a regular hexagonal grid in the plane, as depicted in Figure 3. We obtain a hexagonal grid if, from the nodes of a regular triangular grid of side length 1, the nodes of another triangular grid of side length $\sqrt{3}$ are removed (see Figure 4). Therefore the set of nodes $\mathbf{X}^\diamond$ of the regular hexagonal grid are given by

$$\mathbf{X}^\diamond = \{A\mathbf{j}\}_{\mathbf{j}\in\mathbb{Z}^2}\setminus\{B\mathbf{j}\}_{\mathbf{j}\in\mathbb{Z}^2}$$

where

$$B=\begin{pmatrix} 3/2 & 0 \\ \sqrt{3}/2 & \sqrt{3}\end{pmatrix}$$

and $B\mathbf{j}$, $\mathbf{j}\in\mathbb{Z}^2$, denote the removed nodes.

The quasi-interpolant on the h-scaled hexagonal grid

$$h\mathbf{X}^\diamond = \{hA\mathbf{j}\}_{\mathbf{j}\in\mathbb{Z}^2}\setminus\{hB\mathbf{j}\}_{\mathbf{j}\in\mathbb{Z}^2} \tag{8}$$

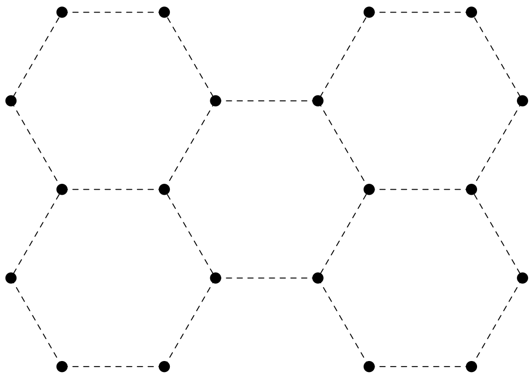

Figure 3: Hexagonal grid

is defined as

$$\mathscr{M}_h^{\diamond} u(\mathbf{x}) := \frac{3\sqrt{3}}{4\mathscr{D}} \sum_{\mathbf{y}^\diamond \in \mathbf{X}^\diamond} u(h\mathbf{y}^\diamond)\, \eta\Big(\frac{\mathbf{x} - h\mathbf{y}^\diamond}{\sqrt{\mathscr{D}}h}\Big).$$

For (8) the quasi-interpolant $\mathscr{M}_h^{\diamond} u$ can be written in an equivalent way

$$\mathscr{M}_h^{\diamond} u(\mathbf{x}) = \frac{3\sqrt{3}}{4\mathscr{D}} \Big(\sum_{\mathbf{j} \in \mathbb{Z}^2} u(hA\mathbf{j}) \eta\Big(\frac{\mathbf{x} - hA\mathbf{j}}{\sqrt{\mathscr{D}}h}\Big) - \sum_{\mathbf{j} \in \mathbb{Z}^2} u(hB\mathbf{j}) \eta\Big(\frac{\mathbf{x} - hB\mathbf{j}}{\sqrt{\mathscr{D}}h}\Big)\Big),$$

Therefore we derive that under the decay conditions and the moment conditions on η the quasi-interpolant $\mathscr{M}_h^{\diamond} u$ provides the estimate (7) for sufficiently large $\mathscr{D}$.

¿From Poisson's summation formula

$$\sum_{\mathbf{j} \in \mathbb{Z}^2} \eta\Big(\frac{\mathbf{x} - A\mathbf{j}}{\sqrt{\mathscr{D}}}\Big) = \frac{\mathscr{D}}{\det A} \Big(1 + \sum_{\nu \in \mathbb{Z}^2 \setminus 0} \mathscr{F}\eta(\sqrt{\mathscr{D}}(A^t)^{-1}\nu)\, \mathrm{e}^{2\pi \mathrm{i}(\mathbf{x},(\mathrm{A}^t)^{-1}\nu)}\Big),$$

we obtain an approximate partition of unity centered at the hexagonal grid:

$$\frac{3\sqrt{3}}{4\mathscr{D}} \sum_{\mathbf{y}^\diamond \in \mathbf{X}^\diamond} \eta\Big(\frac{\mathbf{x} - \mathbf{y}^\diamond}{\sqrt{\mathscr{D}}}\Big) - 1 = \sum_{\mathbf{j} \in \mathbb{Z}^2} \eta\Big(\frac{\mathbf{x} - A\mathbf{j}}{\sqrt{\mathscr{D}}}\Big) - \sum_{\mathbf{j} \in \mathbb{Z}^2} \eta\Big(\frac{\mathbf{x} - B\mathbf{j}}{\sqrt{\mathscr{D}}}\Big) - 1 =$$

$$\frac{3}{2} \sum_{\nu \in \mathbb{Z}^2 \setminus 0} \mathscr{F}\eta(\sqrt{\mathscr{D}}(A^t)^{-1}\nu)\, \mathrm{e}^{2\pi \mathrm{i}(\mathbf{x},(\mathrm{A}^t)^{-1}\nu)} -$$

$$\frac{1}{2} \sum_{\nu \in \mathbb{Z}^2 \setminus 0} \mathscr{F}\eta(\sqrt{\mathscr{D}}(B^t)^{-1}\nu)\, \mathrm{e}^{2\pi \mathrm{i}(\mathbf{x},(\mathrm{B}^t)^{-1}\nu)}.$$

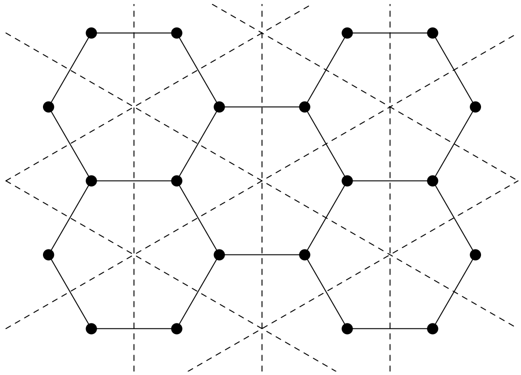

Figure 4: Nodes of a hexagonal grid. The eliminated triangular grid $B\mathbf{j}$ is depicted with dashed lines.

In the case of the exponential $\eta(\mathbf{x}) = \pi^{-1}\mathrm{e}^{-|\mathbf{x}|^2}$ we have estimated the main term of the saturation error by

$$\Big|1 - \frac{3\sqrt{3}}{4\pi\mathscr{D}} \sum_{\mathbf{y}^\diamond \in \mathbf{X}^\diamond} \mathrm{e}^{-|\mathbf{x}-\mathbf{y}^\diamond|^2/\mathscr{D}}\Big| \tag{9}$$

$$\leq \frac{1}{2} \sum_{(\nu_1,\nu_2)\neq(0,0)} \big(3\mathrm{e}^{-4\pi^2\mathscr{D}(\nu_1^2-\nu_1\nu_2+\nu_2^2)/3} + \mathrm{e}^{-4\pi^2\mathscr{D}(\nu_1^2-\nu_1\nu_2+\nu_2^2)/9}\big)$$

$$= 3\,\mathrm{e}^{-4\pi^2\mathscr{D}/9} + \mathscr{O}(\mathrm{e}^{-4\pi^2\mathscr{D}/3}).$$

In Figure 5 the difference (9) is depicted for two different values of $\mathscr{D}$.

3. Results for nonuniform grids

Next we consider an extension of the approximate quasi-interpolation formulas on uniform grid to the case that the data are given on a set of scattered nodes $\mathbf{X} = \{\mathbf{x}_j\} \subset \mathbb{R}^n$ close to a uniform grid in the sense that we specify in Condition 3.1.

Proposition 3.1. *There exists a uniform grid Λ such that the quasi-interpolants*

$$\mathscr{M}_{h,\mathscr{D}}\, u(\mathbf{x}) = \mathscr{D}^{-n/2} \sum_{\mathbf{y}_j \in \Lambda} u(h\mathbf{y}_j)\,\eta\Big(\frac{\mathbf{x}-h\mathbf{y}_j}{h\sqrt{\mathscr{D}}}\Big)$$

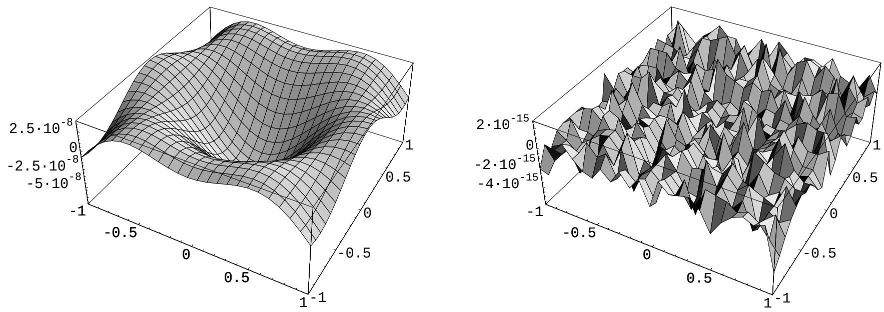

Figure 5: The graph of $\frac{3\sqrt{3}}{4\pi\mathscr{D}}\sum_{\mathbf{y}^\diamond\in\mathbf{X}^\diamond} \mathrm{e}^{-|\mathbf{x}-\mathbf{y}^\diamond|^2/\mathscr{D}} - 1$ when $D = 4$ (on the left) and $D = 8$ (on the right).

approximate sufficiently smooth functions u with the error

$$|\mathscr{M}_{h,\mathscr{D}}u(\mathbf{x}) - u(\mathbf{x})| \leq c_{N,\eta}\,(h\sqrt{\mathscr{D}})^N \|\nabla_N u\|_{L_\infty(\mathbb{R}^n)} + \varepsilon \sum_{k=0}^{N-1} (h\sqrt{\mathscr{D}})^k |\nabla_k u(\mathbf{x})| \quad (10)$$

for any $\varepsilon > 0$.

Let $\mathbf{X}_h$ *be a sequence of grids with the property that for* $\kappa_1 > 0$ *not depending on h and any* $\mathbf{y}_j \in \Lambda$ *the ball* $B(h\mathbf{y}_j, h\kappa_1)$ *contains nodes of* $\mathbf{X}_h$.

For example, if η satisfies the conditions of Theorem 2.1, we may assume as Λ the cubic grid $\{\mathbf{j}\}$ or, in the plane, the triangular grid $\{\mathbf{y}^\triangle\}$ or the hexagonal grid $\{\mathbf{y}^\diamond\}$.

In order to construct an approximate quasi-interpolant which use the data at the nodes of $\mathbf{X}_h$ we introduce the following definition.

Definition 3.2. Let $\mathbf{x}_j \in \mathbf{X}_h$. A collection of $m_N = \dfrac{(N-1+n)!}{n!(N-1)!} - 1$ nodes $\mathbf{x}_k \in \mathbf{X}_h$ will be called *star* of $\mathbf{x}_j$ and denoted by $\mathrm{st}\,(\mathbf{x}_j)$ if the Vandermonde matrix

$$V_{j,h} = \left\{ \left(\frac{\mathbf{x}_k - \mathbf{x}_j}{h} \right)^\alpha \right\}, \ |\alpha| = 1, \ldots, N-1,$$

is not singular.

Proposition 3.3. *Denote by* $\widetilde{\mathbf{x}}_j \in \mathbf{X}_h$ *the node closest to* $h\mathbf{y}_j \in h\Lambda$. *There exists* $\kappa_2 > 0$ *such that for any* $\mathbf{y}_j \in \Lambda$ *the star* $\mathrm{st}\,(\widetilde{\mathbf{x}}_j) \subset B(\widetilde{\mathbf{x}}_j, h\kappa_2)$ *with* $|\det V_{j,h}| \geq c > 0$ *uniformly in h.*

Let us denote by $\{b^{(j)}_{\alpha,k}\}$, $|\alpha| = 1,\dots,N-1$, $\mathbf{x}_k \in \mathrm{st}\,(\widetilde{\mathbf{x}}_j)$, the elements of the inverse matrix of $V_{j,h}$, and consider the functional

$$F_{j,h}(u) = u(\widetilde{\mathbf{x}}_j)\Big(1 - \sum_{|\alpha|=1}^{N-1}\Big(\mathbf{y}_j - \frac{\widetilde{\mathbf{x}}_j}{h}\Big)^{\alpha} \sum_{\mathbf{x}_k\in \mathrm{st}\,(\widetilde{\mathbf{x}}_j)} b^{(j)}_{\alpha,k}\Big) + \sum_{\mathbf{x}_k\in \mathrm{st}\,(\widetilde{\mathbf{x}}_j)} u(\mathbf{x}_k) \sum_{|\alpha|=1}^{N-1} b^{(j)}_{\alpha,k}\Big(\mathbf{y}_j - \frac{\widetilde{\mathbf{x}}_j}{h}\Big)^{\alpha}.$$

The functional $F_{j,h}(u)$ depends on the values of u at the nodes of $\mathrm{st}\,(\widetilde{\mathbf{x}}_j) \cup \widetilde{\mathbf{x}}_j$ *i.e.* $m_N + 1$ points close to $h\mathbf{y_j}$.

Let us define the following quasi-interpolant which uses the values of u on $\mathbf{X}_h$

$$\mathbb{M}_{h,\mathscr{D}}u(\mathbf{x}) = \mathscr{D}^{-n/2} \sum_{\mathbf{y}_j\in\Lambda} F_{j,h}(u)\,\eta\Big(\frac{\mathbf{x} - h\mathbf{y}_j}{h\sqrt{\mathscr{D}}}\Big). \tag{11}$$

The following theorem states that, under the above mentioned conditions on the grid, $\mathbb{M}_{h,\mathscr{D}}u$ has the same behavior as in the case of uniform grids.

Theorem 3.4. ([4]) *Under the Conditions* 3.1 *and* 3.3*, for any* $\varepsilon > 0$ *there exists* $\mathscr{D} > 0$ *such that the quasi-interpolant* (11) *approximates any* $u \in W^N_\infty(\mathbb{R}^n)$ *with*

$$|\mathbb{M}_{h,\mathscr{D}}u(\mathbf{x}) - u(\mathbf{x})| \le c_{N,\eta,\mathscr{D}}\, h^N \|\nabla_N u\|_{L_\infty(\mathbb{R}^n)} + \varepsilon \sum_{k=0}^{N-1} (h\sqrt{\mathscr{D}})^k |\nabla_k u(\mathbf{x})|\,,$$

where $c_{N,\eta,\mathscr{D}}$ *does not depend on u and h.*

One of the motivations of approximate approximations is the construction of cubature formulas for integral operators of convolution type

$$\mathscr{K}u(\mathbf{x}) = \int_{\mathbb{R}^n} k(\mathbf{x} - \mathbf{y})u(\mathbf{y})\,d\mathbf{y}\,. \tag{12}$$

A cubature formula of the multi-dimensional integral (12) can be obtained if the density u is replaced by the quasi-interpolant $\mathbb{M}_{h,\mathscr{D}}u$. Then

$$\mathscr{K}\,\mathbb{M}_{h,\mathscr{D}}u(\mathbf{x}) = \mathscr{D}^{-n/2} \sum_{\mathbf{y}_j\in\Lambda} F_{j,h}(u) \int_{\mathbb{R}^n} k(\mathbf{x} - \mathbf{y})\,\eta\Big(\frac{\mathbf{y} - h\mathbf{y}_j}{h\sqrt{\mathscr{D}}}\Big)d\mathbf{y}$$
$$= h^n \sum_{\mathbf{y}_j\in\Lambda} F_{j,h}(u) \int_{\mathbb{R}^n} k\Big(h\sqrt{\mathscr{D}}\Big(\frac{\mathbf{x} - h\mathbf{y}_j}{h\sqrt{\mathscr{D}}} - \mathbf{y}\Big)\Big)\eta(\mathbf{y})d\mathbf{y}$$

is a cubature formula for (12) with a generating function η chosen such that $\mathscr{K}\eta$ can be computed analytically or at least by some efficient quadrature method.

In (11) the generating function is centered at the nodes of the uniform grid $h\Lambda$. This can be helpful to design fast methods for the approximation of (12). If we define

$$a^{(h)}_{k-j} = \int_{\mathbb{R}^n} k\big(h(\mathbf{y}_k - \mathbf{y}_j - \sqrt{\mathscr{D}}\mathbf{y})\big)\,\eta(\mathbf{y})d\mathbf{y}\,.$$

we reduce to the computation of the following sums

$$\mathscr{K}\,\mathbb{M}_{h,\mathscr{D}}u(h\mathbf{y}_k) = h^n \sum_{\mathbf{y}_j\in\Lambda} F_{j,h}(u)\,a^{(h)}_{k-j}$$

which provide an approximation of (12) at the mesh points $h\mathbf{y}_k$.

A generalization of the method approximate approximations to functions with values given on a rather general grid was obtained in [3].

4. Numerical Experiments

The quasi-interpolant $\mathbb{M}_{h,\mathscr{D}}u$ in (11) was tested by one- and two-dimensional experiments and the results of the numerical experiments confirm the predicted approximation orders. In all cases the grid $\mathbf{X}_h$ is chosen such that any ball $B(h\mathbf{j},h/2)$, $\mathbf{j}\in\mathbb{Z}^n$, $n=1$ or $n=2$, contains one randomly chosen node, which we denote by $\mathbf{x}_\mathbf{j}$.

The one-dimensional case. Figures 6 – 9 show the graphs of $\mathbb{M}_{h,\mathscr{D}}u-u$ for different smooth functions u using the basis function $\eta(x)=\pi^{-1/2}\mathrm{e}^{-x^2}$ (Fig. 6 and 7) for which $N=2$, and $\eta(x)=\pi^{-1/2}(3/2-x^2)\mathrm{e}^{-x^2}$ (Fig. 8 and 9) for which $N=4$, for different values of h. We have chosen the parameter $\mathscr{D}=4$ in order to keep the saturation error less than 10^{-16}.

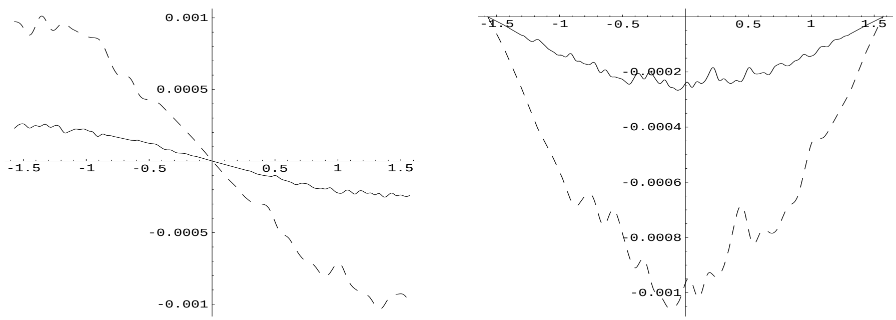

Figure 6: The graphs of $\mathbb{M}_{h,\mathscr{D}}u-u$ with $\eta(x)=\pi^{-1/2}\mathrm{e}^{-x^2}$, $\mathscr{D}=4$, $\mathrm{st}(x_j)=\{x_{j+1}\}$, when $u(x)=\sin(x)$ (on the left) and $u(x)=\cos(x)$. Dashed and solid lines correspond to $h=1/32$ and $h=1/64$.

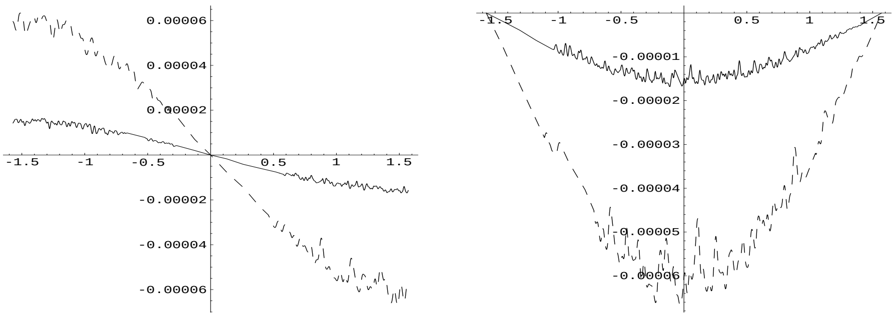

Figure 7: The graphs of $\mathbb{M}_{h,\mathscr{D}}u-u$ with $\eta(x)=\pi^{-1/2}\mathrm{e}^{-x^2}$, $\mathscr{D}=4$, $\operatorname{st}(x_j)=\{x_{j+1}\}$, when $u(x)=\sin(x)$ (on the left) and $u(x)=\cos(x)$. Dashed and solid lines correspond to $h=1/128$ and $h=1/256$.

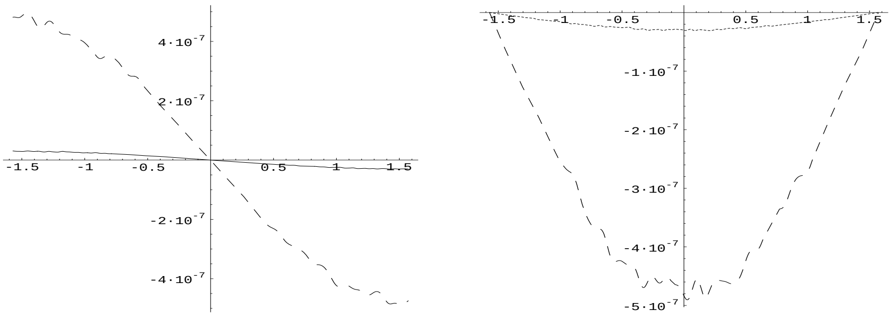

Figure 8: The graphs of $\mathbb{M}_{h,\mathscr{D}}u-u$ with $\eta(x)=\pi^{-1/2}(3/2-x^2)\mathrm{e}^{-x^2}$, $\mathscr{D}=4$, $\operatorname{st}(x_j)=\{x_{j-2},x_{j-1},x_{j+1}\}$, when $u(x)=\sin(x)$ (on the left) and $u(x)=\cos(x)$. Dashed and solid lines correspond to $h=1/32$ and $h=1/64$.

The two-dimensional case. We depict in Figures 10 and 11 the quasi-interpolation error $\mathbb{M}_{h,\mathscr{D}}u-u$ for the function $u(\mathbf{x})=(1+|\mathbf{x}|^2)^{-1}$ and different h if generating functions of second (with $\mathscr{D}=2$) and fourth (with $\mathscr{D}=4$) order of approximation are used. The h^2- and respectively h^4-convergence of the corresponding two-dimensional quasi-interpolants are confirmed by the $L_\infty-$ errors which are given in Table 1.

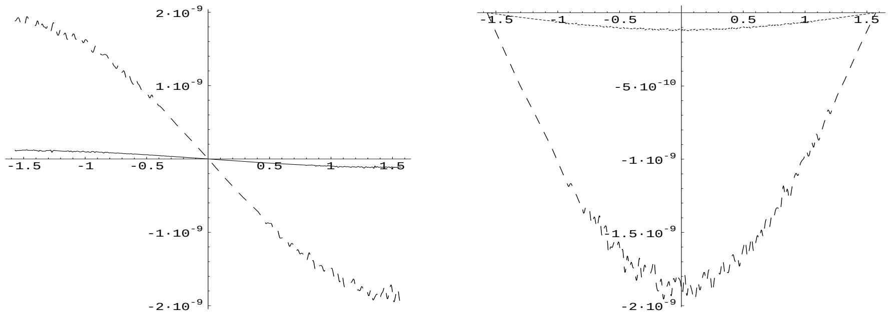

Figure 9: The graphs of $\mathbb{M}_{h,\mathscr{D}}u-u$ with $\eta(x)=\pi^{-1/2}(3/2-x^2)e^{-x^2}$, $\mathscr{D}=4$, $\mathrm{st}(x_j)=\{x_{j-2},x_{j-1},x_{j+1}\}$, when $u(x)=\sin(x)$ (on the left) and $u(x)=\cos(x)$. Dashed and solid lines correspond to $h=1/128$ and $h=1/256$.

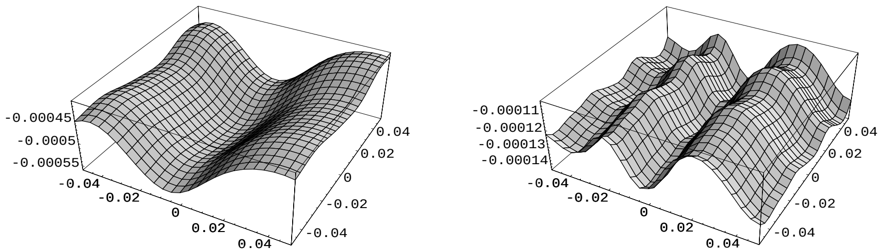

Figure 10: The graph of $\mathbb{M}_{h,\mathscr{D}}u-u$ with $\mathscr{D}=2$, $\eta(\mathbf{x})=\pi^{-1}e^{-|\mathbf{x}|^2}$, $N=2$, $u(\mathbf{x})=(1+|\mathbf{x}|^2)^{-1}$, $h=2^{-6}$ (on the left) and $h=2^{-7}$ (on the right).

h	$\mathscr{D}=2$	$\mathscr{D}=4$
2^{-4}	$8.75\cdot10^{-3}$	$1.57\cdot10^{-2}$
2^{-5}	$2.21\cdot10^{-3}$	$4.00\cdot10^{-3}$
2^{-6}	$5.51\cdot10^{-4}$	$1.01\cdot10^{-3}$
2^{-7}	$1.42\cdot10^{-4}$	$2.52\cdot10^{-4}$
2^{-8}	$3.56\cdot10^{-5}$	$6.50\cdot10^{-5}$

h	$\mathscr{D}=4$	$\mathscr{D}=6$
2^{-4}	$4.42\cdot10^{-4}$	$9.59\cdot10^{-4}$
2^{-5}	$2.95\cdot10^{-5}$	$6.61\cdot10^{-5}$
2^{-6}	$1.92\cdot10^{-6}$	$4.24\cdot10^{-6}$
2^{-7}	$1.24\cdot10^{-7}$	$2.68\cdot10^{-7}$
2^{-8}	$7.80\cdot10^{-9}$	$1.71\cdot10^{-8}$

Table 1: L_∞ approximation error for the function $u(\mathbf{x})=(1+|\mathbf{x}|^2)^{-1}$ using $\mathbb{M}_{h,\mathscr{D}}u$ with $\eta(\mathbf{x})=\pi^{-1}e^{-|\mathbf{x}|^2}$, $N=2$ (on the left), and $\eta(\mathbf{x})=\pi^{-1}(2-|\mathbf{x}|^2)e^{-|\mathbf{x}|^2}$, $N=4$ (on the right).

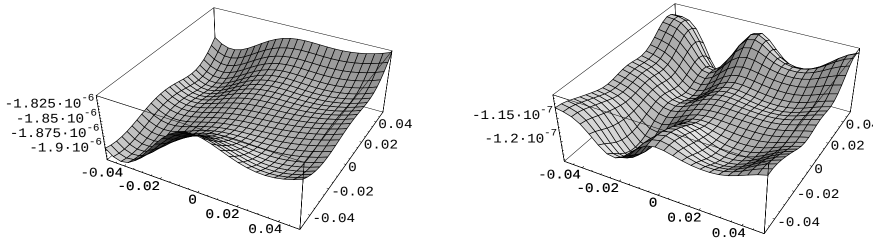

Figure 11: The graph of $\mathbb{M}_{h,\mathscr{D}}u - u$ with $\mathscr{D} = 4$, $\eta(\mathbf{x}) = \pi^{-1}(2 - |\mathbf{x}|^2)e^{-|\mathbf{x}|^2}$, $N = 4$, $u(\mathbf{x}) = (1 + |\mathbf{x}|^2)^{-1}$, $h = 2^{-6}$ (on the left) and $h = 2^{-7}$ (on the right).

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