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An adaptive meshless method of line based on radial basis functions

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Abstract

In this paper, an adaptive meshless method of line is applied to distribute the nodes in the spatial domain. In many cases in meshless methods, it is also necessary for the chosen nodes to have certain smoothness properties. The set of nodes is also required to satisfy certain constraints. In this paper, one of these constraints is investigated. The aim of this manuscript is the implementation of an algorithm for selection of the nodes satisfying a given constraint, in the meshless method of line. This algorithm is applied to some illustrative examples to show the efficiency of the algorithm and its ability to increase the accuracy.

Keywords: Adaptive Meshless Methods; Meshless Method of Line; Radial Basis Functions.

1 Introduction

In the last decade, application of radial basis functions (RBFs) in the meshless methods, for numerical solution of various types of partial differential equations (PDEs) has been developed [9–11]. One of the main advantages of this method is the mesh-free property. Meshless methods do not typically need a mesh. They need some scattered nodes in the domain that can be selected uniformly or randomly. This is one of the important properties of the meshless methods. An alternative meshless method is an approach that uses a mesh to obtain a good set of nodes based on the problem options (such as the form of equation, initial or boundary conditions). These methods are known as adaptive meshless methods. Early researchers have incorporated

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the adaptive methods in several schemes $[1, 28, 29, 34, 36]$. In this paper an adaptive method known as Equidistribution $[7, 14]$ is introduced for selecting a set of nodes under a specified criterion on the set. The criterion is that in the set of nodes, the ratio of the largest distance to the smallest distance must be smaller than a given parameter k. Kautsky and Nichols introduced an algorithm to enforce this criterion in the Equidistribution algorithm [7]. In this research, this algorithm is applied in meshless method of line to improve the accuracy of the method. This paper is presented as follows. In Section 2, radial basis functions are introduced. In Section 3, an adaptive method is described for selecting a set of nodes and an algorithm is introduced based on the given criterion. Section 4, is devoted to presenting some illustrative examples, and comparing the numerical results of uniform and adaptive meshes.

2 Radial basis functions to approximate a function

In this section some essential points about radial basis functions (RBFs), are introduced. For more details, interested readers are referred to [1,9–11,19,37]. Suppose that a real function $u = u(x),\ x \in \mathbb{R}^d$, should be approximated. An approximation to u, by radial basis functions, will be defined as the following

$$u^*(x) = \sum_{j=1}^{N} \lambda_j \, \varphi(\, \|x - x_j\| \,) \qquad \lambda_j \in \mathbb{R}.$$

Where $x, x_j \in \mathbb{R}^d$, and norm is the Euclidean norm, and φ is a RBF on $\mathbb{R}^d$. An RBF is a real valued function which is only dependent on the distance r, between x and a point $x_j \in \mathbb{R}^d (r = \ ||x - x_i||)$. Some of important RBFs are:

$\varphi(r) = \sqrt{1 + \varepsilon^2 r^2}$ Multiquadrics (MQ),

$\varphi(r) = 1/(1 + \varepsilon^2 r^2)$ Inverse Quadratics (IQ),

$\varphi(r) = 1/\sqrt{1 + \varepsilon^2 r^2}$ Inverse Multiquadrics (IMQ),

$\varphi(r) = e^{-\varepsilon^2 r^2}$ Gaussian (GA),

where ε is called the shape parameter. N distinct nodes x_j are called central nodes. In matrix notation, the approximated function $u^*(x)$ is denoted as follows,

$$u^*(x) = \sum_{j=1}^{N} \lambda_j \, \varphi(r_j) = \Phi^t(r) \, \lambda, \tag{1}$$

where

$$\Phi(r) = [\varphi(r_1), \varphi(r_2), ..., \varphi(r_N)]^t, \quad \lambda = [\lambda_1, \lambda_2, ..., \lambda_N]^t, \quad \varphi(r_j) = \varphi(\|x - x_j\|),$$

λ, is the vector of coefficients, that will be determined. By considering $u^*(x_i) = u_i$, equation (1) can be presented as a system of equations $A\lambda = U$, where, $U = [u_1, u_2, ..., u_N]^t$, and by considering $\varphi(r_{ij}) = \varphi(\|x_i - x_j\|)$,

$$A = [\Phi^t(r_1), \Phi^t(r_2), ..., \Phi^t(r_N)]^t,$$

where $\Phi^t(r_i) = [\varphi(r_{i1}), \varphi(r_{i2}), ..., \varphi(r_{iN})]$. By solving the system of equations $A\lambda = U$, the unknown vector λ will be determined. There are several factors affecting the RBF interpolation process, such as central nodes distribution, shape parameter, etc. In this paper our focus is on the central nodes distribution.

3 An adaptive meshless method

3.1 Meshless method of line

Method of line (MOL) is a general method for solving a PDE. In this method, two sequential strategies will be followed: discretizing all directions except one (usually the time direction for time-dependent PDEs) and integrating the semi-discrete problem as a system of ODEs. By choosing RBF collocation method (Kansa Method) [9,10] as integrator system, the method is called the meshless method of line (MMOL). MMOL involves the following main steps:

1- Partitioning the spatial domain (In meshless method of line, this step is reduced to choosing some center nodes x_i in the spatial domain).

2- Discretizing of the problem in one direction (Usually, time direction in time-dependent PDEs).

3- Approximating the solution $u(x, t_n)$ in each step of time by RBF-approximation as follows

$$u(x, t_n) = \sum_{j=1}^{N} \lambda_j \, \varphi(r_j) = \Phi^t(r)\lambda \qquad \lambda_j \in \mathbb{R}. \tag{2}$$

4- Substituting (2) in the governing equation and collocating x_i. This leads to a system of ordinary differential equation.

5- Solving the system of ODEs by suitable method, such as RK4 (In each step of RK4, the solution of the problem in each time step is obtained).

This method is well-addressed in [4, 15].

3.2 Adaptive meshless method of line

In each step of RK4 in MMOL, the center nodes x_i can be selected by an adaptive mesh. Adaptivity is a well-known concept in mesh generation. The purpose of the adaption is to change the center nodes, so that to achieve greater accuracy. As an example, if the problem was approximating a function with a rapid change in some areas of its domain, concentrating the center nodes in these areas could improve the accuracy of the approximation. There are several adaptive algorithms for choosing central nodes in the domain. In this research, methods based on Equidistribution are investigated.

Definition 1. (Equidistribution). Let M is a non-negative piecewise continuous function on $[a, b]$, and c is a constant, such that $n = (1/c)\int_a^b M(x)\,dx$ is an integer. The mesh

$$\Pi : \ a = x_1, x_2, ..., x_n = b,$$

is called equi-distributing (e.d.) on $[a, b]$ with respect to M and c if

$$\int_{x_{i-1}}^{x_i} M(x)\,dx = c\ , \ \ j = 2...n,$$

and is called subequi-distributing (s.e.d.) on $[a, b]$, with respect to M and c if, for $nc \geq \int_a^b M$,

$$\int_{x_{i-1}}^{x_i} M(x)\,dx \leq c, \qquad j = 2\ldots n.$$

A suitable algorithm to produce an e.d. mesh is given in [7]. In the definition 1, the function M, often called a monitor, is dependent on the function u. A well-known monitor function is arc-length monitor. The arc-length monitor is defined as the following

$$M(x) = \sqrt{1 + u_x^2}.$$

To find more details about the monitors and implementation of the algorithm, interested readers are referred to [6, 7, 17].

In [31], Sarra introduced an adaptive algorithm which was developed to RBF methods for interpolation problems and PDEs. He applied the method for time dependent PDEs. The method is a combination of the meshless Method of Line and an Equidistribution algorithm for producing a set of center nodes, in each step. The algorithm is an e.d. one with arc-length monitor. The method is summarized as follows:
In the adaptive algorithm, we start at time t^0 with uniform nodes. To advance the PDE in time with the adaptive grid algorithm the method is implemented

as follows. Assume that $s_j^n,\ j = 1..N$, is approximate solution at time t^n at distinct nodes $x_j^n,\ j = 1..N$. Then, the MMOL is used on these central nodes to obtain approximations $\bar{s}_j^{n+1},\ j = 1..N$, at time t^{n+1}. Next, by an Equidistribution based algorithm, a new set of nodes is obtained based on the properties of $\bar{s}^{n+1}$. To obtain new central nodes, the points $(x_j^n, \bar{s}_j^{n+1})$ are joined by straight lines and the length of the resulting polygon is computed (Figure 1-a, 1-b). Then N equally spaced points on the polygon are found which divide its total length into N equal parts (Figure 1-c). The new nodes $x_j^{n+1},\ j = 1..N$, are found as the projection of these N equally spaced points on the polygon to the x-axis (Figure 1-d). Finally, s_j^{n+1} is obtained by interpolating the values $(x_j^n, \bar{s}_j^{n+1})$. Applying this algorithm, distribute the nodes on the spatial domain based on the approximated solution at each time step, i.e. in step one, the nodes are distributed based on initial condition. If there are regions of steep gradients, it is obvious that the algorithm concentrate the nodes over these regions. In these regions, the nodes will be near together and this fact leads to an ill-conditioned problem. Since condition number of RBF matrix becomes very large or sometimes even close to singular. Thus, based on the Equidistribution mesh without constraint, there is not any guarantee to well-conditioning of the problem. Thus imposing some constraints can be useful to overcome this deficiency. One of these constraints to control the distribution of the nodes in the domain, is as follows

$$\frac{h_{\max}}{h_{\min}} < k, \tag{3}$$

where $h_i = x_i - x_{i-1}$. On the other hand, the introduced algorithm does not work if the constraint be applied. To apply the Equidistribution algorithm subject to this constraint, some modifications must be done. In addition to the investigated constraint, there are some other constraints, such as a constraint introduced by Kautsky and Nichols which is; the ratio of the length of successive subintervals must be less than a parameter k. In this study we investigate the constraint (3). In the following, an algorithm due to Kautsky and Nichols [7] will be introduced to distribute a set of nodes for which the constraint (3) is satisfied.

3.3 An algorithm for the adaptive nodes with constraint

Suppose that $(x_j, s_j),\ j = 1, 2, .., N$ are some data points. Our goal is to gain a set of nodes based on the Equidistribution algorithm that satisfy the constraint (3). Thus, an s.e.d. mesh is produced, with respect to M and c.

Theorem 1. *If* $\Pi :\ \{a = x_1, x_2, ..., x_n = b\}$ *is an e.d. mesh on* $[a, b]$ *with respect to* g *and* d*, where*

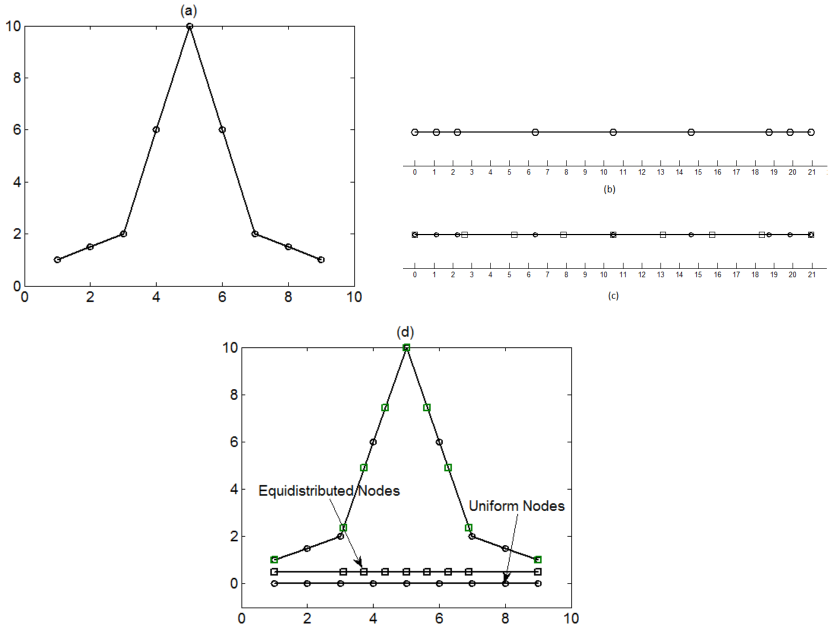

Figure 1: Geometrical interpretation of the Equidistribution procedure

$$g(t) = \max(M(t), p),$$

with

$$p = (1/k) \max_{t\in[a,b]} M(t),$$

and $d = (1/c)\int_a^b g(x)\,dx$ *(and* n *is equal to the smallest integer such that* $nc \geq \int_a^b g$*), then* Π *is a s.e.d. on* $[a,b]$ *with respect to* M *and* c*, and satisfies in* (3)*.*

Proof. For proof and more details about the implementation of the algorithm, see [7].

Figure 2, illustrates the effect of the constraint in the distributing of nodes. The figure also shows the uniform adaptive nodes without constraint, and adaptive nodes with constraint. It is obvious that the constraint omits the huge concentration in a region.

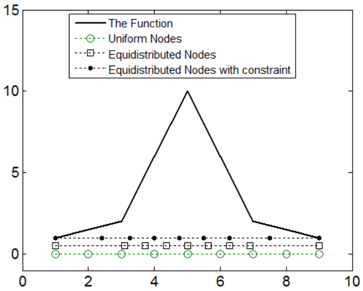

Figure 2: The comparison of three types of distribution for a test function

4 Numerical experiments

In this section, the algorithm is implemented on two time-dependent partial differential equations. The method is a combination of the algorithm which is introduced in 3.1 and Equidistribution algorithm (introduced in 3.3), regarding the constraint (3). In fact, the e.d. algorithm is implemented in each step of time in meshless method of line to produce adaptive central nodes which satisfy the constraint (3).

Example 1. Consider the Burger equation

$$u_t + u\, u_x = \upsilon\, u_{xx}, \tag{4}$$

on the interval [-1,1]. The exact solution is $u(x,t) = \frac{0.1\, e^a + 0.5\, e^b + e^c}{e^a + e^b + e^c}$, where $a = -(x + 0.5 + 4.95t)/(20\upsilon)$, $b = -(x + 0.5 + 0.75t)/(4\upsilon)$, and $c = -(x + 0.625)/(2\upsilon)$. The initial condition $u(x,0)$ and the boundary conditions $u(-1,t)$, $u(1,t)$ are specified. By choosing $\upsilon = 0.0035$, the equation is solved by uniform and adaptive nodes. Meshless method of line combined with adaptive algorithm is applied on equation (4). By choosing N center nodes $\{x_1, x_2, ..., x_N\}$ in the domain [-1,1], at a constant time t, the solution $u(x,t)$ can be expressed in RBF-approximation as follows

$$u(x,t) = \sum_{j=1}^{N} \lambda_j\, \varphi(r_j) = \Phi^t(r)\lambda. \tag{5}$$

Collocating (5) by $\{x_1, x_2, ..., x_N\}$, leads us to the following system of equation

$$A\lambda = u, \tag{6}$$

where $u = [u(x_1,t), u(x_2,t), ..., u(x_N,t)]$. By substituting $\lambda = A^{-1}u$ into (5), we have

$$u(x,t) = \; \Phi^t(r)A^{-1}u = V(x)u(t), \tag{7}$$

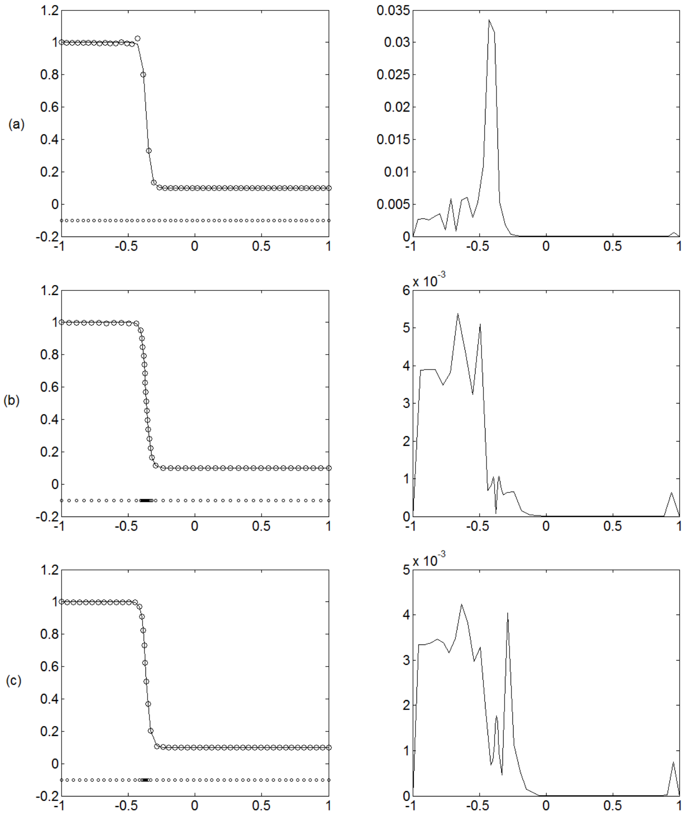

Figure 3: Plots of the approximate solution and absolute error of equation (4) at t=0.5 using 50 uniform nodes (a), adaptive nodes without constraint (b), and adaptive nodes with constraint (c)

where $V(x) = \Phi^t(x)A^{-1} = [V_1(x), ..., V_N(x)]$. By substituting (7) into the Burger equation (4), and collocating the center nodes x_i, we obtain

$$\frac{du_i}{dt} + u_i\left(V_x(x_i)\,u\right) = \upsilon\,\left(V_{xx}(x_i)u\right), \qquad i = 1, 2, ..., N.$$

This equation can be written as a system of ordinary differential equations as

$$\frac{du}{dt} = -u \otimes \left(V_x(x_i)\,u\right) + \upsilon\,\left(V_{xx}(x_i)u\right), \tag{8}$$

where $\otimes$ denote component by component multiplication of two vectors. Equation (8), is rewritten as

$$\frac{du}{dt} = F(u), \tag{9}$$

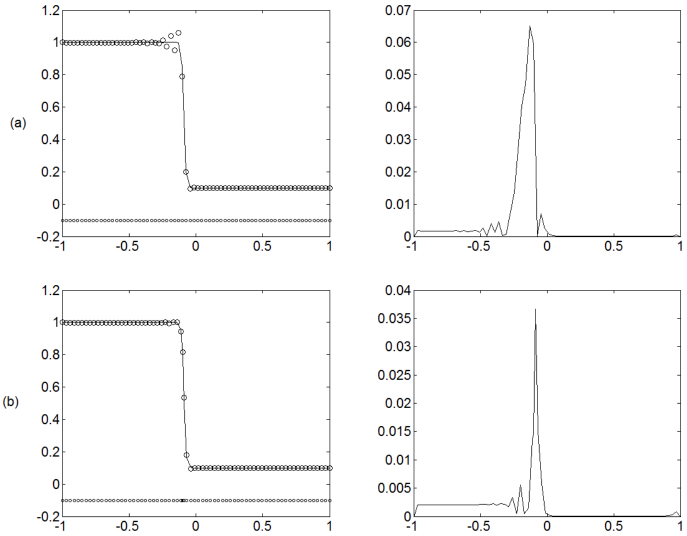

Figure 4: Plots of the approximate solution and absolute error of equation (4) at t=1 using 70 uniform nodes (a), and adaptive nodes with constraint (b)

where $F(u) = -u \otimes (V_x(x_i)\, u) + \upsilon\, (V_{xx}(x_i)u)$. The system of ordinary differential equations (9) can be solved by RK4 method. In the nth step of RK4, $u(x, t_n)$ is approximated. As mentioned before, the center nodes $\{x_1, x_2, ..., x_N\}$ in each step can be selected adaptively. We solve the Burger equation (4), by adaptive meshless method of line by three different distribution of center nodes; uniformly distributed nodes, adaptive nodes without constraints, and adaptive nodes with the constraint (3). Figure 3 shows the approximate solution at t=0.5 with different center nodes. The approximate solution by uniform nodes demonstrates that, it has the minimum accuracy in the sharpest region of the solution. Furthermore Figure 3-b, and 3-c show the same accuracy for two adaptive center nodes. It is important that without constraint (3), the condition number of the RBF matrix may be very large (close to singular) or singular, and RBF interpolation can't work exactly. Due to this fact, in this example at time 1, by 70 adaptive nodes without constraint, the method is failed to obtain a solution (Table 1). The results of using uniform nodes and adaptive nodes with constraint are shown in Figure 4. Table 1 illustrates the accuracy of the adaptive algorithm. It is known that the value of the parameter k influence the concentration of the nodes. Thus to illustrate the impact of the parameter k in distributing the adaptive nodes, and in the accuracy of the results, the error norm by different values of this parameter are investigated in Table 1.

Table 1: The error norms of the approximate solution of Example 1

t	N	Distribution of nodes	k	ε	Max error	RMS error	Figure
0.5	50	Uniform	-	31	0.0335	0.0070	Figure 3-a
		Adaptive without constraint	-	31	0.0054	0.0018	Figure 3-b
		Adaptive with constraint	2	31	0.0307	0.0064	-
			3	31	0.0154	0.0036	-
			6	31	0.0042	0.0018	Figure 3-c
0.5	70	Uniform	-	31	0.0059	0.0013	-
		Adaptive without constraint	-	31	0.0027	0.0011	-
		Adaptive with constraint	2	31	0.0023	9.65e-4	-
			3	31	0.0019	8.81e-4	-
			6	31	0.0022	0.0010	-
1	70	Uniform	-	31	0.0650	0.0135	Figure 4-a
			-	51	0.0942	0.0166	-
		Adaptive without constraint	-	31	NaN	NaN	-
			-	51	NaN	NaN	-
		Adaptive with constraint	3	31	0.3548	0.0509	-
			3	51	0.0367	0.0055	Figure 4-b
			6	31	0.0321	0.0067	-
			6	51	0.0435	0.0087	-

Example 2. Consider the KdV equation

$$u_t + \varepsilon u\, u_x + \mu\, u_{xxx} = 0, \tag{10}$$

with $\varepsilon = 6$, and $\mu = 1$. The initial condition is

$$u(x,0) = 2\ \sec h^2(x).$$

The exact solution is

$$u(x,t) = 2\ \sec h^2(x - 4t).$$

The computational domain is$[-10, 40]$. The boundary conditions $u(-10,t)$ and $u(40,t)$ are determined. This problem is solved by the same method as the example 1. Figure 5 shows the solution of the equation (10), with uniform and adaptive center nodes. It is obvious that, by 110 center nodes, at t=0.5, the approximate solutions using adaptive nodes have better accuracy. The RMS error and Max-error of the results (Table 2), shown that the adaptive nodes with constraint result in better accuracy. If the number of central nodes increased up to 150, the solutions by adaptive nodes have the same accuracy. It is predictable, because when the number of nodes is large, the e.d. algorithm leads to nearly uniform distribution of nodes and consequently, the errors of approximate solutions are close. Table 2, demonstrate the impact of N, k, and shape parameter ε, in the accuracy of the results.

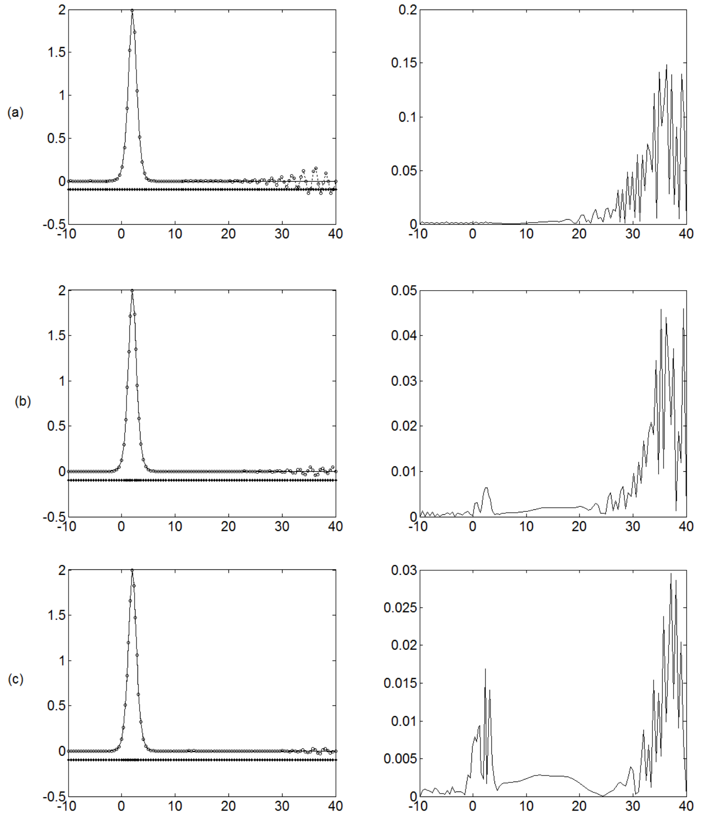

Figure 5: Plots of the approximate solution and absolute error of equation (10) at t=0.5 using 110 uniform nodes (a), adaptive nodes without constraint (b), and adaptive nodes with constraint (c)

Table 2: The error norms of the approximate solution of Example 2

t	N	Distribution of nodes	k	ε	Max error	RMS error	Figure
0.5	110	Uniform	-	0.8	0.1485	0.0389	Figure 5-a
		Adaptive without constraint	-	0.9	0.0460	0.0110	Figure 5-b
		Adaptive with constraint	2	1.2	0.0295	0.0069	Figure 5-c
			3	1.2	0.0295	0.0069	-
			6	1.2	0.0295	0.0069	-
0.5	150	Uniform	-	0.8	0.0205	0.0065	-
		Adaptive without constraint	-	0.8	0.0046	0.0014	-
		Adaptive with constraint	2	0.8	0.0033	0.0010	-
			3	0.8	0.0033	0.0010	-
			6	0.8	0.0033	0.0010	-
1	150	Uniform	-	0.8	0.0197	0.0094	-
			-	1.1	0.0074	0.0034	-
		Adaptive without constraint	-	0.8	0.0045	0.0021	-
			-	1.1	0.0054	0.0025	-
		Adaptive with constraint	2	0.8	0.0033	0.0016	-
			2	1.1	0.0030	0.0014	-
			3	0.8	0.0033	0.0016	-
			3	1.1	0.0030	0.0014	-

5 Conclusion

In this paper, an Equidistribution algorithm has been applied to distribute the central nodes in adaptive modes to RBF methods. To have some smoothness properties, by the e.d. algorithm, the central nodes satisfying in a given constraint are obtained. This method was applied to two nonlinear time-dependent partial differential equations by MMOL. In numerical examples, the results obtained by uniform nodes, and adaptive nodes with, and without the constraint have been compared. The numerical results in Example 1, reveal that with adaptive nodes, a more accurate approximate solution has been obtained. Our numerical experience shows that, in this example, to achieve the accuracy as good as adaptive nodes, at least 150 uniform nodes must be applied. Also in Example 2, with 110 uniform nodes, the obtained results by adaptive nodes with constraint have better accuracy. With 150 center nodes a good accuracy has been obtained by three distributions. The numerical results in the examples illustrate the efficiency of adaptive nodes to solving some nonlinear PDEs with MMOL. The results show that applying the adaptive central nodes is more accurate in the problems with speed gradient functions.

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یک روش خط بدون شبکه سازگار بر اساس توابع پایه شعاعی

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چکیده : در این مقاله، از یک روش خط بدون شبکه سازگار برای توزیع نقاط در دامنه فضایی استفاده می شود. در روش های بدون شبکه، در موارد بسیاری لازم است که نقاط انتخاب شده شرایط همواری خاصی داشته باشند و مجموعه نقاط در محدودیت هایی صدق کند. در این مقاله، یکی از این محدودیت ها بررسی می شود. هدف از این مطالعه، به کار بردن الگوریتمی در روش خط بدون شبکه است برای انتخاب نقاطی که در شرایطی مشخص، صدق کنند. برای نشان دادن کارایی الگوریتم و توانایی آن در افزایش دقت، آنرا در تعدادی مثال نمونه به کار می بریم.

کلمات کلیدی : روش های بدون شبکه سازگار؛ روش خط بدون شبکه؛ توابع پایه شعاعی.