

A New Class of Odd-point Ternary Non-Stationary Schemes

Ghulam Mustafa* and Mehwish Bari†

Department of Mathematics
The Islamia University of Bahawalpur

Abstract

In this paper we generate a new family of odd point ternary non-stationary interpolating subdivision schemes by using Lagrange identities. It is to be observed that the limiting ellipse, generated by proposed schemes compared to the existing non-stationary interpolating schemes, has less deviation from being an exact ellipse. The proposed non-stationary schemes are asymptotically equivalent to converging stationary schemes [1, 3, 9, 11, 13, 14]. The performance and comparison of the schemes are verified by examples.

Keywords: Subdivision; Interpolation; Non-stationary; Smoothness; Tension control; Conics reproduction

1 Introduction

Subdivision defines a curve or surface from an initial control mesh by recursive refinement. Starting with the coarse control points $F^0 = \{f_n^0 | n \in \mathbb{Z}^d\}$, recursive application of the subdivision rule S_k defines a new set of points $F^k = \{f_n^k | n \in \mathbb{Z}^d\}$ which can be written as

$$F^k = S_k \dots S_0 F^0, \quad k \in \mathbb{Z}_+. \quad (1.1)$$

Here, a subdivision scheme is said to be stationary if S_k is the same regardless of k ; otherwise it is called non-stationary [4]. The important schemes for applications should allow to control the shape of the limit curve and be capable of reproducing

*Corresponding author: ghulam.mustafa@iub.edu.pk.

†mehwishbari@yahoo.com.

This work is supported by the Indigenous Ph. D Scholarship Scheme of Higher Education Commission (HEC) Pakistan.

families of curves widely used in Computer Graphics, such as conic sections and polynomials. Effectiveness of subdivision algorithms, their flexibility and ease make them appropriate for many relative computer graphics applications.

Here we present brief survey of existing literature. Jena et al. [4] proposed a 4-point binary non-stationary interpolating scheme. This scheme reproduces elements of the linear space spanned by $\{1, \sin(\alpha x), \cos(\alpha x)\}$. Beccari et al. [6] proposed a non-stationary uniform tension controlled interpolating 4-point scheme with a single tension parameter having C^1 continuity. Daniel and Shunmugaraj [8] presented 3-point C^1 stationary and non-stationary schemes. They also proposed C^2 non-stationary approximating scheme in [10] and 4-point ternary interpolating non-stationary scheme [12] spanned by $\{1, \sin(\alpha x), \cos(\alpha x)\}$. Beccari et al. [15] proposed 4-point ternary non-stationary interpolating scheme with tension control. They proposed the shape controlled ternary interpolatory subdivision in [16]. Further they presented the interpolating and approximating univariate subdivision by a unified framework [17]. Conti et al. [18] proposed approximating to interpolatory non-stationary subdivision schemes with the same generation properties. In [19], they also design interpolatory subdivision schemes by solving Bezout-like polynomial equations. Conti and Romani [20] presented algebraic conditions on non-stationary subdivision symbols for exponential polynomial reproduction. Charina et al. [21] proposed reproduction of exponential polynomials by multivariate non-stationary subdivision schemes with a general dilation matrix. Further more, there are some other well known schemes [2, 5, 7, 12] in the literature suitable for generating basic shapes in computer graphics.

However the existing non-stationary ternary interpolating schemes are the counterpart of existing stationary schemes (without parameter) but our proposed schemes are non-stationary counterpart of existing parametric stationary schemes. This property give advantage to control the shape of limit curve than the schemes without parameter.

We have compared the existing non-stationary ternary schemes, suitable to generate ellipse, with proposed schemes. We adopt the following strategy:

- Introduce deviation error function
- Refine initial control polygon with 4, 5 and 6 initial control points by different non-stationary schemes to generate ellipse
- Compute deviation error and compare the results

We conclude that the limiting ellipse to be an exact ellipse, generated by proposed scheme, has less deviation error compare to the limiting ellipse produced by the different non-stationary ternary schemes.

This paper is organized as follows. In Section 2, we construct some results which are useful for Section 3. In Section 3, we present odd point non-stationary

ternary interpolating schemes providing the user with a tension parameter that, when increased within its range of definition, can generate continuous limit curves showing considerable variations. Section 3 also provides the convergence of proposed interpolating schemes. Section 4 is devoted for comparison and conclusion.

2 Preliminaries

Given a set of control points $F^0 = \{f_i^0 \in \mathbb{R} : i \in \mathbb{Z}\}$ at level 0, a ternary subdivision scheme for designing curves generates recursively a new set of control points $F^{k+1} = \{f_i^{k+1} : i \in \mathbb{Z}\}$ at the $(k+1)^{th}$ level by a subdivision rule:

$$f_i^{k+1} = \sum_{j \in \mathbb{Z}} a_{i-3j}^k f_j^k, \quad i \in \mathbb{Z}.$$

The set of coefficients $a^k = \{a_i^k : i \in \mathbb{Z}\}$ determines the subdivision rule at level k and is termed as the mask at k -th level. If the masks a^k is independent of k , the subdivision scheme S_{a^k} corresponding to the mask a^k is called stationary otherwise it is called non-stationary.

Theorem 2.1. [2] Two ternary schemes S_{a^k} and S_{b^k} are asymptotically equivalent if

$$\sum_{k=1}^{\infty} \|S_{a^k} - S_{b^k}\| < \infty,$$

where

$$\|S_{a^k}\|_{\infty} = \max \left\{ \sum_{i \in \mathbb{Z}} |a_{3i}^k|, \sum_{i \in \mathbb{Z}} |a_{3i+1}^k|, \sum_{i \in \mathbb{Z}} |a_{3i+2}^k| \right\}.$$

The proof of the following theorem is exactly similar by [12] to the proof given in (Theorem 8, [2]).

Theorem 2.2. Let S_{a^k} and S_a be two asymptotically equivalent subdivision schemes having finite masks of the same support. Suppose S_{a^k} is non-stationary and S_a is stationary. If S_a is C^m and

$$\sum_{k=0}^{\infty} 3^{mk} \|S_{a^k} - S_a\|_{\infty} < \infty,$$

then the non-stationary scheme S_{a^k} is C^m .

Deslauriers and Dubuc [1] presented the idea to construct subdivision schemes using Lagrange interpolation. Here we also use Lagrange polynomial to construct non-stationary schemes. First we define Lagrange fundamental polynomials of

degree $2n-2$ and $2n-3$, for any integer $n \geq 1$, corresponding to nodes $\{x_j\}_{-(n-1)}^{n-1}$ and $\{x_j\}_{-(n-1)}^{n-2}$ respectively,

$$L_{x_m}^{2n-2}(x) = \prod_{x_j=-(n-1), x_m \neq x_j}^{n-1} \frac{x - x_j}{x_m - x_j}, \quad x_m = -(n-1), -(n-2), \dots, (n-1), \quad (2.1)$$

and

$$L_{x_m}^{2n-3}(x) = \prod_{x_j=-(n-2), x_m \neq x_j}^{n-1} \frac{x - x_j}{x_m - x_j}, \quad x_m = -(n-2), -(n-3), \dots, (n-1). \quad (2.2)$$

By using algebraic operations, we get following expressions:

$$\beta_1 = L_{x_m}^{2n-2} \left(\frac{1}{3} \right) = \frac{(-1)^{n-1} (3n-2)!}{3^{3n-3} (1-3x_m)(n-1)!}, \quad (2.3)$$

$$\beta_2 = L_{x_m}^{2n-3} \left(\frac{1}{3} \right) = \frac{(-1)^{n-1} (3n-4)!}{3^{3n-5} (1-3x_m)(n-2)!} = \frac{\tau_1}{\tau_2}. \quad (2.4)$$

Further, for $x_m = -n+1$ in (2.3), we get

$$\beta_3 = L_{-n+1}^{2n-2} \left(\frac{1}{3} \right) = \frac{(-1)^{-n+1} (3n-3)!}{3^{3n-3} (n-1)! (2n-2)!}. \quad (2.5)$$

Furthermore, we have

$$\tau_3 = \beta_1 - \beta_2 = \frac{(-1)^{x_m} (3n-3)!}{3^{3n-3} (n-1)! (n-x_m-1)! (n+x_m-1)!}. \quad (2.6)$$

$$A_{x_m} = \frac{\beta_1 - \beta_2}{\beta_3} = \frac{\tau_3}{\beta_3}. \quad (2.7)$$

For more detail, we may refer to [14]. By perturbing expression (2.4) and (2.7) with sin function we get

$$\tilde{A}_{n,x_m} = \frac{\sin \left(\frac{\tau_1}{3^{k+1}} \right)}{\sin \left(\frac{\tau_2}{3^{k+1}} \right)}, \quad (2.8)$$

$$\hat{A}_{n,x_m} = \frac{\sin \left(\frac{\tau_3}{3^{k+1}} \right)}{\sin \left(\frac{\beta_3}{3^{k+1}} \right)}, \quad (2.9)$$

where $x_m = -n+2, \dots, n-1$ and $n \geq 1$ is any integer.

3 $(2n - 1)$ -point ternary interpolating scheme

In this section, we present general explicit formulae to construct the mask of $(2n - 1)$ -point ternary interpolating subdivision scheme.

Given $n \geq 2$, the mask of following $(2n - 1)$ -point ternary interpolating scheme

$$\begin{cases} f_{3i-1}^{k+1} = \sum_{x_m=-(n-1)}^{n-1} \eta_{-x_m}^{k,2n-1} f_{i+x_m}^k, \\ f_{3i}^{k+1} = f_i^k, \\ f_{3i+1}^{k+1} = \sum_{x_m=-(n-1)}^{n-1} \eta_{x_m}^{k,2n-1} f_{i+x_m}^k, \end{cases} \quad (3.1)$$

can be generated by

$$\begin{cases} \eta_{-n+1}^{k,2n-1} = \frac{\sin(\frac{\omega}{3^{k+1}})}{\sin(\frac{1}{3^{k+1}})}, & \omega < 1, \\ \eta_{x_m}^{k,2n-1} = \tilde{A}_{n,x_m} + \hat{A}_{n,x_m} \omega, & x_m = -n+2, \dots, n-1, \end{cases} \quad (3.2)$$

where $\tilde{A}_{n,x_m}$ and $\hat{A}_{n,x_m}$ are defined by (2.8) and (2.9).

Examples:

Substituting $n = 2$ in (3.1) and (3.2), we get new 3-point ternary interpolating scheme with free parameter ω

$$\begin{aligned} f_{3i-1}^{k+1} &= \eta_1^{k,3} f_{i-1}^k + \eta_0^{k,3} f_i^k + \eta_{-1}^{k,3} f_{i+1}^k, \\ f_{3i}^{k+1} &= f_i^k, \\ f_{3i+1}^{k+1} &= \eta_{-1}^{k,3} f_{i-1}^k + \eta_0^{k,3} f_i^k + \eta_1^{k,3} f_{i+1}^k, \end{aligned} \quad (3.3)$$

where

$$\begin{aligned} \eta_{-1}^{k,3} &= \frac{\sin\left(\frac{\omega}{3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)}, \\ \eta_0^{k,3} &= \frac{\sin\left(\frac{2}{3 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} - \frac{\sin\left(\frac{2}{9 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{9 \cdot 3^{k+1}}\right)} \omega \end{aligned}$$

and

$$\eta_1^{k,3} = \frac{\sin\left(\frac{1}{3 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} + \omega.$$

Substituting $n = 3$ in (3.1) and (3.2), we get new 5-point ternary interpolating scheme with free parameter ω

$$\begin{aligned} f_{3i-1}^{k+1} &= \eta_2^{k,5} f_{i-2}^k + \eta_1^{k,5} f_{i-1}^k + \eta_0^{k,5} f_i^k + \eta_{-1}^{k,5} f_{i+1}^k + \eta_{-2}^{k,5} f_{i+2}^k, \\ f_{3i}^{k+1} &= f_i^k, \\ f_{3i+1}^{k+1} &= \eta_{-2}^{k,5} f_{i-2}^k + \eta_{-1}^{k,5} f_{i-1}^k + \eta_0^{k,5} f_i^k + \eta_1^{k,5} f_{i+1}^k + \eta_2^{k,5} f_{i+2}^k, \end{aligned} \quad (3.4)$$

where

$$\begin{aligned}\eta_{-2}^{k,5} &= \frac{\sin\left(\frac{\omega}{3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)}, \\ \eta_{-1}^{k,5} &= \frac{\sin\left(\frac{1}{3^{k+1}}\left[-\frac{5}{81} - 4\omega\right]\right)}{\sin\left(\frac{1}{3^{k+1}}\right)}, \\ \eta_0^{k,5} &= \frac{\sin\left(\frac{1}{3^{k+1}}\left[\frac{20}{27} + 6\omega\right]\right)}{\sin\left(\frac{1}{3^{k+1}}\right)}, \\ \eta_1^{k,5} &= \frac{\sin\left(\frac{1}{3^{k+1}}\left[\frac{10}{27} - 4\omega\right]\right)}{\sin\left(\frac{1}{3^{k+1}}\right)}\end{aligned}$$

and

$$\eta_2^{k,5} = \frac{\sin\left(\frac{1}{3^{k+1}}\left[-\frac{4}{81} + \omega\right]\right)}{\sin\left(\frac{1}{3^{k+1}}\right)}.$$

Remark 3.1. The sum of weights of the scheme (3.3) tends to one as $k \rightarrow \infty$.

$$\xi^k = \eta_{-1}^{k,3} + \eta_0^{k,3} + \eta_1^{k,3} = \frac{\sin\left(\frac{\omega}{3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} + \frac{\sin\left(\frac{2}{3 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} - \frac{\sin\left(\frac{2}{9 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{9 \cdot 3^{k+1}}\right)}\omega + \frac{\sin\left(\frac{1}{3 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} + \omega.$$

This implies

$$\xi^k = \frac{\sin\left(\frac{\omega}{3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} + \frac{\sin\left(\frac{2}{3 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} - 2\omega \cos\left(\frac{1}{9 \cdot 3^{k+1}}\right) + \frac{\sin\left(\frac{1}{3 \cdot 3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} + \omega.$$

Using the inequalities $\sin a \geq a \cos a$ for $0 \leq a \leq \frac{\pi}{2}$, $\frac{1}{\sin a} \geq \frac{1}{a}$ for $0 \leq a \leq \frac{\pi}{2}$, we have

$$\xi^k \geq \frac{\frac{\omega}{3^{k+1}} \cos\left(\frac{\omega}{3^{k+1}}\right)}{\frac{1}{3^{k+1}}} + \frac{\frac{2}{3 \cdot 3^{k+1}} \cos\left(\frac{2}{3 \cdot 3^{k+1}}\right)}{\frac{1}{3^{k+1}}} - 2\omega \cos\left(\frac{1}{9 \cdot 3^{k+1}}\right) + \frac{\frac{1}{3 \cdot 3^{k+1}} \cos\left(\frac{1}{3 \cdot 3^{k+1}}\right)}{\frac{1}{3^{k+1}}} + \omega.$$

This implies

$$\xi^k \geq \omega \cos\left(\frac{\omega}{3^{k+1}}\right) + \left(\frac{2}{3}\right) \cos\left(\frac{2}{3 \cdot 3^{k+1}}\right) - 2\omega \cos\left(\frac{1}{9 \cdot 3^{k+1}}\right) + \left(\frac{1}{3}\right) \cos\left(\frac{1}{3 \cdot 3^{k+1}}\right) + \omega.$$

Thus $\xi^k \geq 1$ when $k \rightarrow \infty$.

Again, using inequalities $\csc a \leq \frac{1}{a \cos a}$ for $0 \leq a \leq \frac{\pi}{2}$, $\sin a \leq a$ for $0 \leq a \leq \frac{\pi}{2}$, we have

$$\xi^k \leq \frac{\frac{\omega}{3^{k+1}}}{\frac{1}{3^{k+1}} \cos\left(\frac{1}{3^{k+1}}\right)} + \frac{\frac{2}{3 \cdot 3^{k+1}}}{\frac{1}{3^{k+1}} \cos\left(\frac{1}{3^{k+1}}\right)} - 2\omega \cos\left(\frac{1}{9 \cdot 3^{k+1}}\right) + \frac{\frac{1}{3 \cdot 3^{k+1}}}{\frac{1}{3^{k+1}} \cos\left(\frac{1}{3^{k+1}}\right)} + \omega.$$

This implies

$$\xi^k \leq \frac{\omega}{\cos\left(\frac{1}{3^{k+1}}\right)} + \frac{2}{3 \cos\left(\frac{1}{3^{k+1}}\right)} - 2\omega \cos\left(\frac{1}{9 \cdot 3^{k+1}}\right) + \frac{1}{3 \cos\left(\frac{1}{3^{k+1}}\right)} + \omega.$$

Thus $\xi^k \leq 1$ when $k \rightarrow \infty$. So $\xi^k = 1$ for $k \rightarrow \infty$.

Similarly, the sum of weights of the scheme (3.4) tends to one as $k \rightarrow \infty$.

3.1 Convergence of 3- and 5-point ternary schemes

Here first we prove some lemmas by using following inequalities:-

$\frac{\sin a}{\sin b} \geq \frac{a}{b}$ for $0 < a \leq b < \frac{\pi}{2}$, $a \csc a < b \csc b$ for $0 < a < b < \frac{\pi}{2}$ and $\cos a < \frac{\sin a}{a}$ (or $\csc a < \frac{1}{a \cos a}$) for $0 < a < \frac{\pi}{2}$. Then with the help of these lemmas we will show that proposed non-stationary schemes are asymptotically equivalent to existing stationary schemes.

Lemma 3.1.

For 3-point non-stationary scheme (3.3) following inequalities hold:

$$\begin{aligned} (i) \quad \omega &\leq \eta_{-1}^{k,3} \leq \frac{\omega}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (ii) \quad \frac{2}{3} - 2\omega &\leq \eta_0^{k,3} \leq \frac{2}{3 \cos\left(\frac{1}{3^{k+1}}\right)} - \frac{2\omega}{\cos\left(\frac{1}{9 \cdot 3^{k+1}}\right)} \\ (iii) \quad \frac{1}{3} + \omega &\leq \eta_1^{k,3} \leq \frac{1}{3 \cos\left(\frac{1}{3^{k+1}}\right)} + \omega. \end{aligned}$$

Proof. We present the proof of (i) and the proof of (ii) and (iii) are similar. Note that

$$\frac{\sin\left(\frac{\omega}{3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} \geq \frac{\frac{\omega}{3^{k+1}}}{\frac{1}{3^{k+1}}} = \omega.$$

Again consider

$$\frac{\sin\left(\frac{\omega}{3^{k+1}}\right)}{\sin\left(\frac{1}{3^{k+1}}\right)} \leq \frac{\omega}{3^{k+1}} \csc\left(\frac{1}{3^{k+1}}\right) \leq \frac{\frac{\omega}{3^{k+1}}}{\frac{1}{3^{k+1}} \cos\left(\frac{1}{3^{k+1}}\right)} = \frac{\omega}{\cos\left(\frac{1}{3^{k+1}}\right)}.$$

This proves (i).

From Lemma 3.1, we get following lemma.

Lemma 3.2.

For scheme (3.3) with $\omega = -\frac{1}{3} + u$, for $u \in (\frac{2}{9}, \frac{1}{3})$, we have

$$\begin{aligned} (i) \quad -\frac{1}{3} + u &\leq \gamma_{-1}^{k,3} \leq \frac{-\frac{1}{3} + u}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (ii) \quad \frac{4}{3} - 2u &\leq \gamma_0^{k,3} \leq \frac{\frac{4}{3} - 2u}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (iii) \quad u &\leq \gamma_1^{k,3} \leq \frac{u}{\cos\left(\frac{1}{3^{k+1}}\right)}. \end{aligned}$$

Lemma 3.3.

For scheme (3.3) following inequalities also hold:

$$\begin{aligned} (i) \quad |\eta_{-1}^{k,3} - \omega| &\leq C_0 \left(\frac{1}{3^{2k}}\right) \\ (ii) \quad |\eta_0^{k,3} - (\frac{2}{3} - 2\omega)| &\leq C_1 \left(\frac{1}{3^{2k}}\right) \\ (iii) \quad |\eta_1^{k,3} - (\frac{1}{3} + \omega)| &\leq C_2 \left(\frac{1}{3^{2k}}\right) \end{aligned}$$

where constants C_0 , C_1 and C_2 are independent of k .

Proof. The inequality (i) can be proved by using (i) of Lemma 3.1:

$$|\eta_{-1}^{k,3} - \omega| = \omega \left[\frac{1 - \cos\left(\frac{1}{3^{k+1}}\right)}{\cos\left(\frac{1}{3^{k+1}}\right)} \right] \leq \omega \left[\frac{2 \sin^2\left(\frac{1}{2 \cdot 3^{k+1}}\right)}{\cos\left(\frac{1}{3^{k+1}}\right)} \right] \leq \left(\frac{1}{4}\right) \left(\frac{2\omega}{3^{2k+2} \cos\left(\frac{1}{3^{k+1}}\right)} \right).$$

This implies

$$|\eta_{-1}^{k,3} - \omega| \leq \left(\frac{1}{3^{2k}}\right) \left(\frac{\omega}{18 \cos(1)} \right) \leq e_0 \left(\frac{1}{3^{2k}}\right).$$

The proofs of (ii) and (iii) are similar.

From Lemma 3.3, we get following lemma.

Lemma 3.4.

For scheme (3.3) with $\omega = -\frac{1}{3} + u$, for $u \in (\frac{2}{9}, \frac{1}{3})$, following inequalities hold:

$$(i) |\eta_{-1}^{k,3} - (-\frac{1}{3} + u)| \leq \acute{C}_0 \left(\frac{1}{3^{2k}}\right)$$

$$(ii) |\eta_0^{k,3} - (\frac{4}{3} - 2u)| \leq \acute{C}_1 \left(\frac{1}{3^{2k}}\right)$$

$$(iii) |\eta_1^{k,3} - u| \leq \acute{C}_2 \left(\frac{1}{3^{2k}}\right)$$

where constants $\acute{C}_0$, $\acute{C}_1$ and $\acute{C}_2$ are independent of k .

Remark 3.2. From (i)-(iii) of Lemma 3.4, we observe that

$$\eta_{-1}^{k,3} \rightarrow -\frac{1}{3} + u, \quad \eta_0^{k,3} \rightarrow \frac{4}{3} - 2u \quad \text{and} \quad \eta_1^{k,3} \rightarrow u, \quad \text{as } k \rightarrow \infty.$$

This means that the mask of the scheme (3.3) with $\omega = -\frac{1}{3} + u$, for $u \in (\frac{2}{9}, \frac{1}{3})$ converge to the mask of the scheme [11].

Similarly, it is to be mentioned that for $n = 2$, $\omega = a$ where $a = b - \frac{1}{3}$, $\omega = -\frac{1}{9}$, $\omega = -\frac{1}{3} + u$ and $\omega = -\frac{1}{3} + u$ in (3.1), (3.2) and by proving/using similar inequalities like in Lemma 3.1 and Lemma 3.3, we get non-stationary counter part of stationary schemes of [3, 9, 11, 14] respectively.

Theorem 3.5. The proposed 3-point non-stationary scheme (3.3) with $\omega = -\frac{1}{3} + u$, $u \in (\frac{2}{9}, \frac{1}{3})$ is C^1 .

Proof. We claim that

$$\sum_{k=0}^{\infty} 3^k \|S_{a^k} - S_a\|_{\infty} < \infty,$$

where

$$\|S_{a^k} - S_a\|_{\infty} = \max \left\{ \sum_{j \in \mathbb{Z}} |a_{i-3j}^k - a_{i-3j}| : i \in 0, 1, 2 \right\}.$$

From scheme S_{a^k} defined by (3.3) with $\omega = -\frac{1}{3} + u$ and scheme S_a of [11]

$$\sum_{k=0}^{\infty} 3^k \|S_{a^k} - S_a\|_{\infty} = \sum_{k=0}^{\infty} 3^k \left\{ \left| \eta_{-1}^{k,3} - \left(-\frac{1}{3} + u \right) \right| + \left| \eta_0^{k,3} - \left(\frac{4}{3} - 2u \right) \right| + \left| \eta_1^{k,3} - u \right| \right\}.$$

From (i) of Lemma 3.4, it follows that

$$\sum_{k=0}^{\infty} 3^k |\eta_{-1}^{k,3} - (-\frac{1}{3} + u)| \leq \sum_{k=0}^{\infty} 3^k C'_0 \left(\frac{1}{3^{2k}} \right) < \infty.$$

Similarly from (ii) and (iii) of Lemma 3.4, we see that other terms are also less than ∞ . Hence $\sum_{k=0}^{\infty} 3^k \|S_{a^k} - S_a\|_{\infty} < \infty$. Since stationary scheme of [11] is C^1 therefore by Theorem 2.2, proposed scheme (3.3) with $\omega = -\frac{1}{3} + u$ is C^1 . $\square$

Now we will discuss the continuity of 5-point scheme (3.4). For this first we will prove the following lemmas. Proof of these lemmas are similar to the proof of Lemmas 3.1-3.4.

Lemma 3.6.

For 5-point non-stationary scheme (3.4), following inequalities hold:

$$\begin{aligned} (i) \quad & \omega \leq \eta_{-2}^{k,5} \leq \frac{\omega}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (ii) \quad & -\frac{5}{81} - 4\omega \leq \eta_{-1}^{k,5} \leq -\frac{5}{81 \cos\left(\frac{6}{3^{k+1}}\right)} - \frac{4\omega}{\cos\left(\frac{5}{243 \cdot 3^{k+1}}\right)} \\ (iii) \quad & \frac{20}{27} + 6\omega \leq \eta_0^{k,5} \leq \frac{20}{27 \cos\left(\frac{2}{3^{k+1}}\right)} + \frac{6\omega}{\cos\left(\frac{5}{243 \cdot 3^{k+1}}\right)} \\ (iv) \quad & \frac{10}{27} - 4\omega \leq \eta_1^{k,5} \leq \frac{10}{27} - 4\omega \cos\left(\frac{20}{243 \cdot 3^{k+1}}\right) \\ (v) \quad & -\frac{4}{81 \cos\left(\frac{6}{3^{k+1}}\right)} + \omega \leq \eta_2^{k,5} \leq -\frac{4}{81} + \omega \end{aligned}$$

From Lemma 3.6, we get following lemma:

Lemma 3.7.

For scheme (3.4) with $\omega = \frac{4}{81} + u$, for $u \in (-\frac{5}{108}, -\frac{7}{162})$, we have

$$\begin{aligned} (i) \quad & \frac{4}{81} + u \leq \eta_{-2}^{k,5} \leq \frac{\frac{4}{81} + u}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (ii) \quad & -\frac{7}{27} - 4u \leq \eta_{-1}^{k,5} \leq \frac{-\frac{7}{27} - 4u}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (iii) \quad & \frac{28}{27} + 6u \leq \eta_0^{k,5} \leq \frac{\frac{28}{27} + 6u}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (iv) \quad & \frac{14}{81} - 4u \leq \eta_1^{k,5} \leq \frac{\frac{14}{81} - 4u}{\cos\left(\frac{1}{3^{k+1}}\right)} \\ (v) \quad & u \leq \eta_2^{k,5} \leq \frac{u}{\cos\left(\frac{1}{3^{k+1}}\right)} \end{aligned}$$

Lemma 3.8.

For scheme (3.4) following inequalities also hold:

$$\begin{aligned}
(i) \quad & \left| \eta_{-2}^{k,5} - \omega \right| \leq g_0 \left(\frac{1}{3^{2k}} \right) \\
(ii) \quad & \left| \eta_{-1}^{k,5} - \left(-\frac{5}{81} - 4\omega \right) \right| \leq g_1 \left(\frac{1}{3^{2k}} \right) \\
(iii) \quad & \left| \eta_0^{k,5} - \left(\frac{20}{27} + 6\omega \right) \right| \leq g_2 \left(\frac{1}{3^{2k}} \right) \\
(iv) \quad & \left| \eta_1^{k,5} - \left(\frac{10}{27} - 4\omega \right) \right| \leq g_3 \left(\frac{1}{3^{2k}} \right) \\
(v) \quad & \left| \eta_2^{k,5} - \left(-\frac{4}{81} + \omega \right) \right| \leq g_4 \left(\frac{1}{3^{2k}} \right)
\end{aligned}$$

where constants g_0, g_1, g_2, g_3 and g_4 are independent of k .

From Lemma 3.8, we get following lemma.

Lemma 3.9.

For scheme (3.4) with $\omega = \frac{4}{81} + u$, for $u \in (-\frac{5}{108}, -\frac{7}{162})$, following inequalities hold:

$$\begin{aligned}
(i) \quad & \left| \eta_{-2}^{k,5} - \left(\frac{4}{81} + u \right) \right| \leq g'_0 \left(\frac{1}{3^{2k}} \right) \\
(ii) \quad & \left| \eta_{-1}^{k,5} - \left(-\frac{7}{27} - 4u \right) \right| \leq g'_1 \left(\frac{1}{3^{2k}} \right) \\
(iii) \quad & \left| \eta_0^{k,5} - \left(\frac{28}{27} + 6u \right) \right| \leq g'_2 \left(\frac{1}{3^{2k}} \right) \\
(iv) \quad & \left| \eta_1^{k,5} - \left(\frac{14}{81} - 4u \right) \right| \leq g'_3 \left(\frac{1}{3^{2k}} \right) \\
(v) \quad & \left| \eta_2^{k,5} - u \right| \leq g'_4 \left(\frac{1}{3^{2k}} \right)
\end{aligned}$$

where constants g'_0, g'_1, g'_2, g'_3 and g'_4 are independent of k .

Remark 3.3. It is to be noted that for negative values of ω , the trigonometric inequalities does not affect the proof of our main Lemmas 3.3 and Lemma 3.8.

Remark 3.4. From (i)-(v) of Lemma 3.9, we observe that the mask of scheme (3.4) with $\omega = \frac{4}{81} + u$, $u \in (-\frac{5}{108}, -\frac{7}{162})$ converge to the mask of the scheme S_a of [11].

$$\begin{aligned}
& \eta_{-2}^{k,5} \rightarrow \frac{4}{81} + u, \quad \eta_{-1}^{k,5} \rightarrow -\frac{7}{27} - 4u, \quad \eta_0^{k,5} \rightarrow \frac{28}{27} + 6u, \quad \eta_1^{k,5} \rightarrow \frac{14}{81} - 4u \\
& \text{and } \eta_2^{k,5} \rightarrow u, \quad \text{as } k \rightarrow \infty.
\end{aligned}$$

Similarly, for $n = 3$, $\omega = \frac{5}{243}$, $\omega = \frac{4}{81} + u$ and $\omega = \frac{4}{81} + u$ in (3.1), (3.2) and using similar inequalities as in Lemma 3.6 and Lemma 3.8, the proposed (3.4) scheme becomes non-stationary counterpart of the 5-point stationary schemes of [9, 11, 14] respectively.

Theorem 3.10. *The proposed 5-point non-stationary scheme (3.4) with $\omega = \frac{4}{81} + u$, for $u \in (-\frac{5}{108}, -\frac{7}{162})$ is C^2 .*

Proof. From scheme S_{a^k} defined by (3.4) with $\omega = \frac{4}{81} + u$, $u \in (-\frac{5}{108}, -\frac{7}{162})$ and scheme S_a of [11]

$$\sum_{k=0}^{\infty} 3^{2k} \|S_{a^k} - S_a\|_{\infty} = \sum_{k=0}^{\infty} 3^{2k} \left\{ \left| \eta_{-2}^k - \left(\frac{4}{81} + u \right) \right| + \left| \eta_{-1}^k - \left(-\frac{7}{27} - 4u \right) \right| + \left| \eta_0^k - \left(\frac{28}{27} + 6u \right) \right| + \left| \eta_1^k - \left(\frac{14}{81} - 4u \right) \right| + \left| \eta_2^k - u \right| \right\}.$$

By using inequalities (i)-(v) of Lemma (3.9), we see that $\sum_{k=0}^{\infty} 3^{2k} \|S_{a^k} - S_a\|_{\infty} < \infty$. Since stationary scheme of [11] is C^2 therefore by Theorem 2.2, proposed scheme (3.4) is C^2 .

Remark 3.5. Relation with DD schemes: The proposed non stationary ternary interpolating schemes are counter part of stationary DD schemes [1].

- From Lemma 3.1 and Lemma 3.3 with $\omega=0$ and $k \rightarrow \infty$, we get 2-point ternary DD interpolating scheme.
- For $\omega=0$ and $k \rightarrow \infty$ in Lemma 3.6 and Lemma 3.8, we get 4-point ternary DD interpolating scheme. Similarly, we get other DD ternary schemes.

4 Comparison and conclusion

First we generate conic sections by using proposed schemes then we present comparison among proposed and existing non-stationary interpolating schemes. If the initial control points are chosen as values at equidistant points of a function $f(x) \in \text{span}\{\cos(\beta x), \sin(\beta x)\}$, $0 < \beta < \pi$, then the limit function of the scheme is the original function. In particular, if the initial control points are equidistance points and lie on a circle or an ellipse, the scheme generates a circle or an ellipse respectively.

Numerical Examples: Here we take the set of equidistant points $f_i^0 = (a \cos(\frac{2m\pi}{N}), b \sin(\frac{2m\pi}{N}))$, $i \in \mathbb{Z}$, and $m = 0, 1, 2, \dots, N$, $N \geq 4$, as control points of initial control polygons of proposed 3-, 5-point non-stationary schemes. For $a = 2, b = 1$, limiting curves generated by 3-, 5-point schemes are ellipses shown in Fig 1(a) and 1(b). It is observed that for large values of ω limit curves generated by proposed 3-point scheme passes near the initial control polygon whereas for small values of ω limit curves generated by proposed 5-point scheme passes near the initial control polygon as shown in Fig 1(a) and 1(b).

Analogously, by choosing a set of equidistant points from the parabolic equation ($y^2 = 4ax$) for $a = 1$ and hyperbolic equation ($\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$) where $a = 3, b = 2$ then limit curve is parabola and hyperbola as shown in Figure 2(a) and 2(b).

Comparison:

In following, we numerically compare the exactness of limiting ellipses generated by different non-stationary subdivision schemes by using following function.

$$D_k = \|\max \{f_i^k\} - \min \{f_i^k\}\|, \quad (4.1)$$

where

$$f_i^k = \sqrt{(x_i^k + c)^2 + (y_i^k)^2} + \sqrt{(x_i^k - c)^2 + (y_i^k)^2}, \quad \text{for} \quad b^2 \equiv a^2 - c^2 \quad (4.2)$$

where f_i^k are control points generated by subdivision scheme at k -th level of iteration for $k \geq 0$. If the initial control points f_i^0 lie on the ellipse then of course D_0 will be zero. If $D_k = 0$ for sufficiently large k then its mean scheme produce exact ellipse. If $D_k \neq 0$ then f_i^k do not lie on same ellipse. Since D_k measures the maximum deviation of limiting ellipse from being an exact ellipse therefore we can present comparison among different limiting ellipses generated by proposed and existing non-stationary schemes.

By taking four, five and six initial control points, we first generate limiting ellipses by proposed 3-, 5-point and existing non-stationary schemes of [4, 6, 7, 12, 15, 16] then we compute deviation error D_k . Deviation of proposed 3-, 5-point ternary non-stationary interpolating schemes is calculated at parametric values -0.1122, 0.0228, respectively.

- In case of 4 initial control points: Limiting ellipses produced by different non-stationary are shown in Figure 3(a-e) while deviation errors in graphical form are shown in Figure 5(a) and Figure 5(b).
- In case of 5 initial control points: Limiting ellipses are depicted in Figure 3(f-j) while graphical representation of deviation errors are shown in Figure 5(c) and 5(d).
- In case of 6 initial control points: Limiting ellipses are painted in Figure 4(a-e) while graphical representation of deviation errors are shown in Figure 5(e) and 5(f).

Deviation error in limiting ellipses, produced by different schemes with 4, 5 and 6 initial control points, in tabular form are shown in Table 1. From these figures and tables it is clear that the limiting ellipses to be an exact ellipses, generated by proposed scheme, have less deviation compare to the limiting ellipses produced by the schemes of [4, 6, 7, 12, 15, 16].

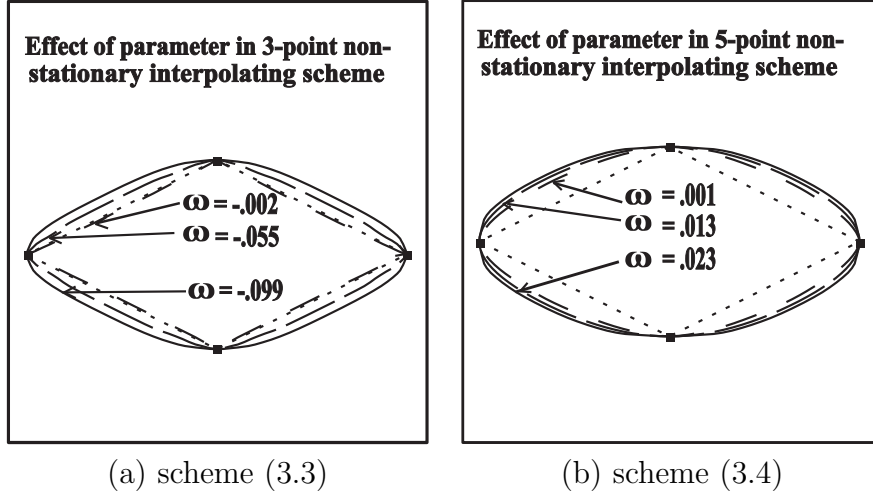


Figure 1: (a) Shows the increase in tightness of the curve with increasing ω and (b) Shows the increase in tightness of the curve with decreasing ω .

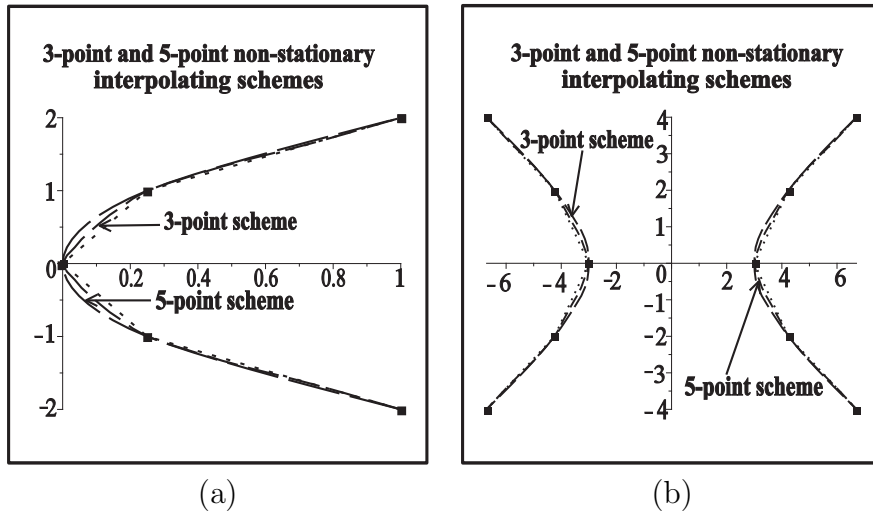
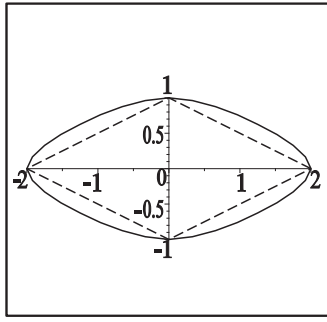
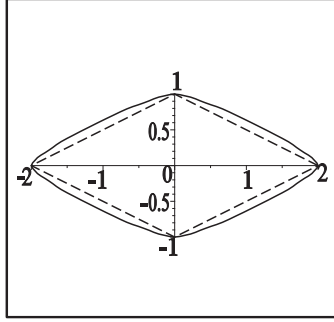


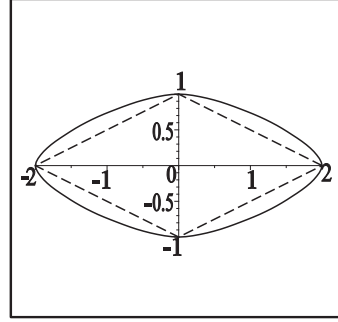
Figure 2: Represents parabola and hyperbola by **proposed** 3-, 5-point non-stationary interpolating schemes after two iterations.



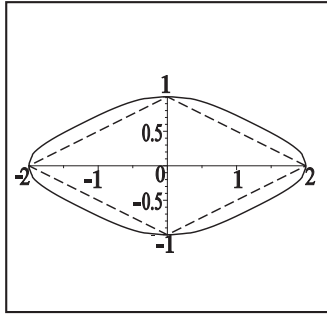
(a) $[4, 6, 7]$



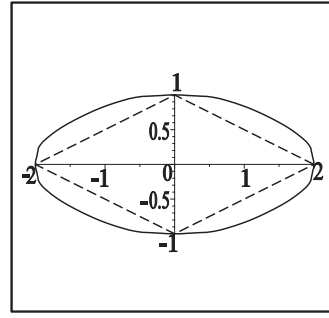
(b) $[7]$



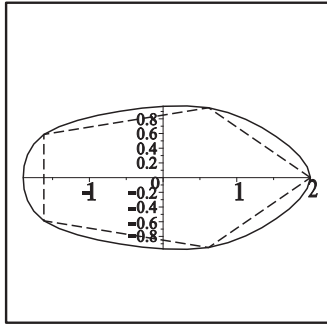
(c) $[12]$



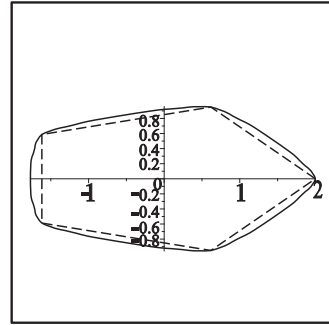
(d) scheme (3.3)



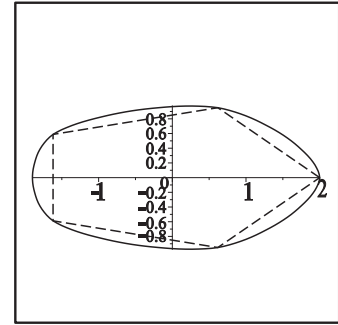
(e) scheme (3.4)



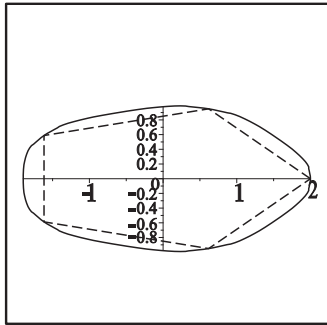
(f) $[4, 6, 7]$



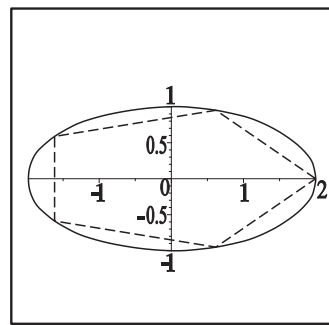
(g) $[7]$



(h) $[12]$



(i) scheme (3.3)



(j) scheme (3.4)

Figure 3: (a) Shows the ellipse produced by non-stationary binary schemes of $[4, 6, 7]$, (b), (g), (c) and (h) show the ellipse produced by non-stationary ternary schemes of $[7, 12]$, (d), (i), (e) and (j) show the ellipse produced by proposed 3-, 5-point non-stationary interpolating schemes respectively.

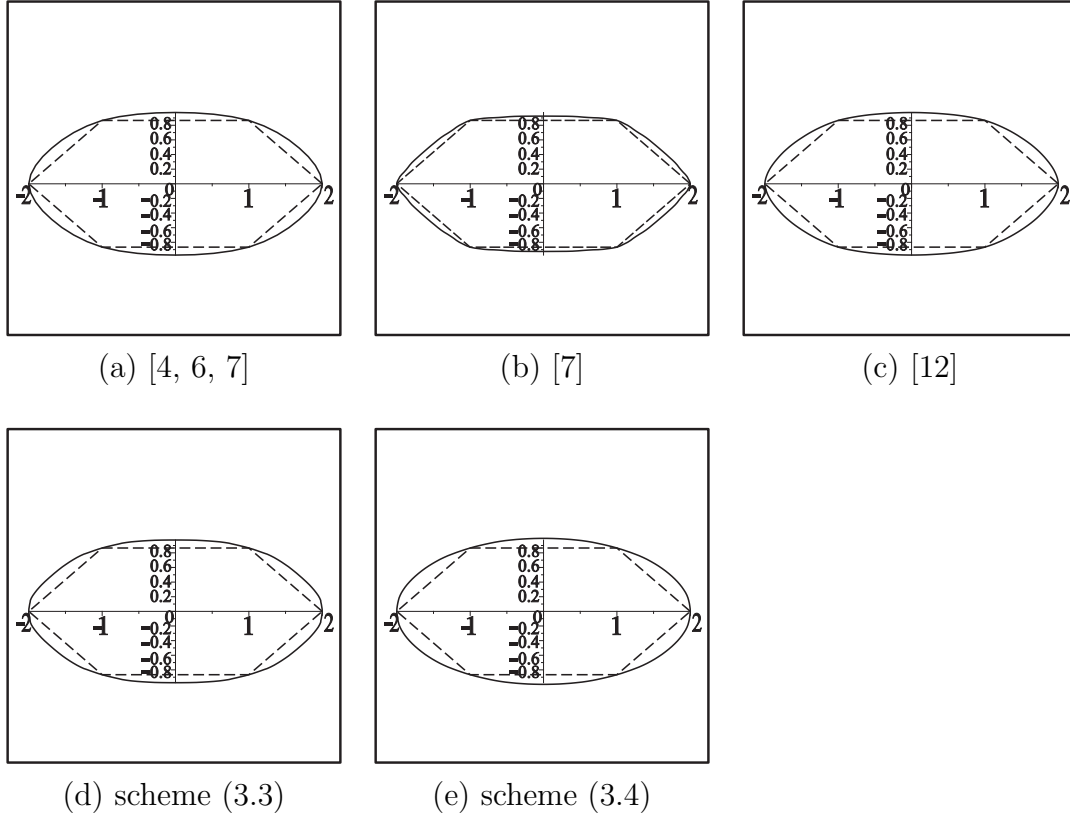
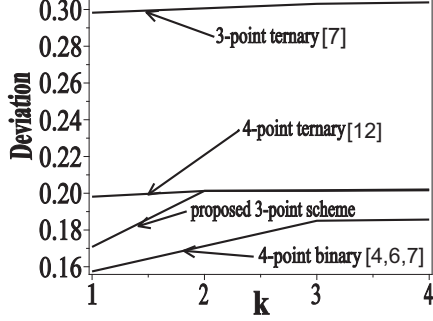


Figure 4: (a) Shows the ellipse produced by non-stationary binary scheme of $[4, 6, 7]$, (b)-(c) show the ellipse produced by non-stationary ternary scheme of $[7, 12]$, (e) and (f) show the ellipse produced by proposed 3-, 5-point non-stationary ternary interpolating schemes respectively.

Table 1: Comparison of deviation error (D. Error) with existing non-stationary interpolating schemes: Here N represents the number of initial points of control polygon.

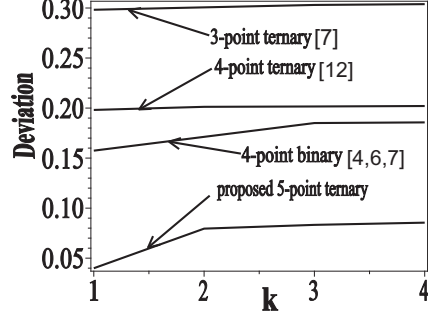
Schemes	N	D. Error	N	D. Error	N	D. Error
4-point binary $[4, 6, 7]$	4	0.18501	5	0.20398	6	0.05910
3-point ternary $[7]$	4	0.30308	5	0.44910	6	0.17196
4-point ternary $[12]$	4	0.20160	5	0.20399	6	0.06478
4-point ternary $[15]$	4	0.19510	5	0.20365	6	0.06219
4-point ternary $[16]$	4	0.20165	5	0.20409	6	0.06483
3-point proposed	4	0.18957	5	0.19579	6	0.05865
5-point proposed	4	0.08104	5	0.04937	6	0.01106

Comparison of proposed 3-point interpolating scheme with existing interpolating schemes



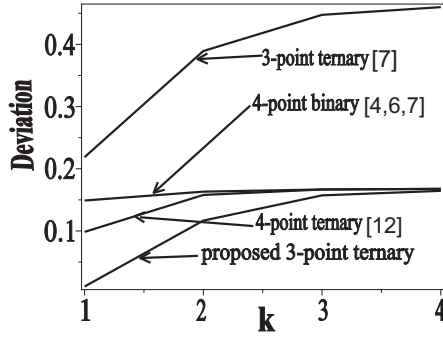
(a) 4 initial points

Comparison of proposed 5-point interpolating scheme with existing interpolating schemes



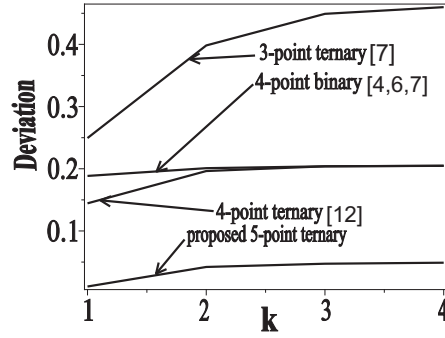
(b) 4 initial points

Comparison of proposed 3-point interpolating scheme with existing interpolating schemes



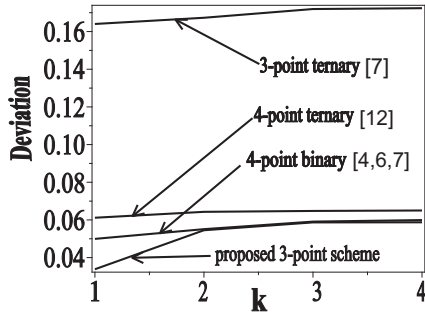
(c) 5 initial points

Comparison of proposed 5-point interpolating scheme with existing interpolating schemes



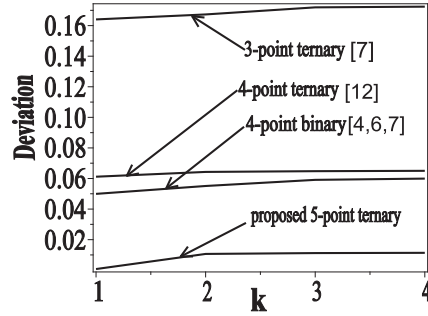
(d) 5 initial points

Comparison of proposed 3-point interpolating scheme with existing interpolating schemes



(e) 6 initial points

Comparison of proposed 5-point interpolating scheme with existing interpolating schemes



(f) 6 initial points

Figure 5: Graphs show the deviation of proposed and existing non-stationary interpolating schemes.

4.1 Conclusions

By using Lagrange identities we construct new families of univariate, ternary, non-stationary interpolating subdivision schemes for curve design with a single tension parameter which enable the scheme to produce more precise result. The proposed schemes are non-stationary counterpart of the stationary schemes [1, 3, 9, 11, 13, 14] so the parametric ranges of continuity of proposed non-stationary schemes are same as of the counter stationary schemes. Figure 1 illustrates that the proposed scheme gives great flexibility to geometric designers for the creation of smooth curves according to their own requirements by choosing appropriate value of parameter.

References

- [1] G. Deslauriers and S. Dubuc, Symmetric iterative interpolation processes, *Constructive Approximation*, 5: 49-68, 1989.
- [2] N. Dyn and D. Levin, Analysis of asymptotically equivalent binary subdivision schemes, *Journal of Mathematical Analysis and Applications*, 193: 594-621, 1995.
- [3] M. F. Hassan and N. A. Dodgson, Ternary and three-point univariate subdivision schemes, in: A. Cohen, J. L. Marrien, L. L. Schumaker (Eds.), *Curve and Surface Fitting: Sant-Malo 2002*, Nashboro Press, Brentwood, 199-208, 2003.
- [4] M. K. Jena, P. Shunmugaraj and P. C. Das, A non stationary subdivision scheme for curve interpolation, *ANZIAM Journal*, 44(E), 216-235, 2003.
- [5] M. Jeon, D. Han, K. Park and G. Choi, Ternary univariate curvature-preserving subdivision, *Journal of Applied Mathematics and Computing*, 18, 235-246, 2005.
- [6] C. Beccari, G. Casciola and L. Romani, A non-stationary uniform tension controlled interpolating 4-point scheme reproducing conics, *CAGD*, 24(1), 1-9, 2007.
- [7] S. Daniel and P. Shunmugaraj, Some non-stationary subdivision schemes, *Geometric Modeling and Imaging (GMAI'07)*, 33-38, 2007, doi:10.1109/GMAI.2007.30.
- [8] S. Daniel and P. Shunmugaraj, Three point stationary and non-stationary subdivision schemes, *3rd International Conference on Geometric Modeling and Imaging*, doi: 10.1109/GMAI.2008.13, 2008.

- [9] Jian-ao-Lian, On a -ary subdivision for curve design: 3-point and 5-point interpolatory schemes, *Applications and Applied Mathematics*, 3, 176-187, 2008.
- [10] S. Daniel and P. Shunmugaraj, An approximating C^2 non-stationary subdivision schemes, *Computer Aided Geometric Design: An International Journal*, 26: 810-821, 2009.
- [11] H. Zheng, M. Hu and G. Peng, Constructing $2n-1$ -point ternary interpolatory subdivision schemes by using variation of constants, *Computational Intelligence and Software Engineering*, 1-4, 2009, doi: 10.1109/CISE.2009.5364446.
- [12] S. Daniel and P. Shunmugaraj, Some interpolating non-stationary subdivision schemes, *International Symposium on Computer Science and Society*, 400-403, 2011, doi 10.1109/ISCCS.2011.110.
- [13] G. Mustafa, A. Ghaffar and F. Khan, The Odd-Point Ternary Approximating Schemes, *American Journal of Computational Mathematics*, 1(2), 111-118, 2011, doi: 10.4236/ajcm.2011.12011.
- [14] M. Aslam, G. Mustafa and A. Ghaffar, $(2n-1)$ -point Ternary Approximating and Interpolating Subdivision Schemes, *Journal of Applied Mathematics*, Vol. 2011, Article ID 832630, 13 pages, 2011.
- [15] C. V. Beccari, G. Casciola, L. Romani, An interpolating 4-point C^2 ternary non-stationary subdivision scheme with tension control, *Computer Aided Geometric Design*, 24, 210-219, 2007.
- [16] C. V. Beccari, G. Casciola, L. Romani, Shape controlled interpolatory ternary subdivision, *Applied Mathematics and Computation*, 215, 916-927, 2009.
- [17] C. V. Beccari, G. Casciola, L. Romani, A unified frame work for interpolating and approximating univariate subdivision, *Applied Mathematics and Computation*, 216, 1169-1180, 2010.
- [18] C. Conti, L. Gemignani, L. Romani, From approximating to interpolatory non-stationary subdivision schemes with the same generation properties, *Advances in Computational Mathematics*, Vol 35, Number 2-4, 217-241, 2011.
- [19] C. Conti, L. Gemignani, L. Romani, Solving Bezout-like polynomial equations for the design of interpolatory subdivision schemes, *ISSAC'10 Proceedings of the 2010 International Symposium on Symbolic and Algebraic Computation*, 251-256, 2010, doi: 10.1145/1837934.1837983.
- [20] C. Conti, L. Romani, Algebraic conditions on non-stationary subdivision symbols for exponential polynomial reproduction, *Journal of Computational and Applied Mathematics*, 236, 543-556, 2011.

- [21] M. Charina, C. Conti, L. Romani, Reproduction of exponential polynomials by multivariate non-stationary subdivision schemes with a general dilation matrix, <http://arxiv.org/pdf/1303.1678.pdf>