In the present work, we introduce two novel root-finding algorithms for nonlinear scalar equations. Among these algorithms, the second one is optimal according to Kung-Traub’s conjecture. It is established that the newly proposed algorithms bear the fourth- and sixth-order of convergence. To show the effectiveness of the suggested methods, we provide several real-life problems associated with engineering sciences. These problems have been solved through the suggested methods, and their numerical results proved the superiority of these methods over the other ones. Finally, we study the dynamics of the proposed methods using polynomiographs created with the help of a computer program using six cubic-degree polynomials and then give a detailed graphical comparison with similar existing methods which shows the supremacy of the presented iteration schemes with respect to convergence speed and other dynamical aspects.

1. Introduction

A huge number of complicated problems in mathematics and engineering disciplines are directly connected to the solution of transcendental and algebraic nonlinear equations of the form:

$$
\varphi(x) = 0,
$$

where the real-valued function $\varphi$ is defined on the open connected set. Mostly, the direct solution of these problems is not possible to find via analytical methods, and ultimately, we have to move towards the iterative algorithms. By an algorithm, we mean a sequence of finite number of steps to achieve the required goal (solution) of the given problem. The repetition of these steps is called iterations. In the process of iterative algorithms, we always need a starting point to initialize the iteration process. This starting point is usually called the initial guess that is rectified after each iteration till the required accuracy is gained.

In literature, there is a plethora of root-finding iterative algorithms for the problems related to the nonlinear equations. The oldest, classical, and most widely used algorithm was suggested by Newton–Raphson in 1690 [1]. Geometrically, the derivation of Newton’s algorithm was purely based on the concept of slope of the line. This method requires two evaluations per iteration and possesses the quadratic convergence order. For many years, Newton’s method has been implemented successfully for root-finding of nonlinear problems. After that, Gutierrez and Hernández [2] presented a new family of Chebyshev–Halley type methods in Banach spaces which were utilized for root-finding of nonlinear problems. In 1993, Argyros et al. [3] discussed the applications of Halley method in Banach space. After few years, Chun [4] constructed Newton-like iteration methods which were purely designed for finding one-dimensional nonlinear equations’ solution. After the construction of one step Newton-like iterative algorithms, a huge class of researchers tried to modify it and suggested a broad range of root-finding algorithms with the help of different mathematical techniques and established a class of multistep algorithm. For further details of the multistep algorithm, one can see Amiri et al. [5], Behl et al. [6], Naseem et al. [7], and Ozypicici [8]. The motivation behind these modifications is to attain higher-order and more efficient algorithms.
study complexity as follows: After that, Gholib and Javidi [12] in 2007 presented a new cubically convergent method whose derivation is totally based on the homotopy-perturbation method. By utilizing the new series expansion of the nonlinear function, Noor et al. [15], in 2012, constructed and then analyzed some novel two-step iteration methods and discussed some special cases. These suggested schemes possessed the convergence of quadratic and cubic orders and were actually the modified form of Newton’s algorithm. Kumar et al. [16] presented a novel class of sixth-order parameter-based methods for finding zeros of one-dimensional nonlinear equations in 2018. In 2019, Said Solaiman et al. [17] proposed derivative free optimal fourth-order and eighth-order versions of King’s approach by combining the composition technique with rational interpolation, as well as the Padé’s concept of approximation. In 2020, Chand et al. [18] developed some novel PotraPtak type optimal sixth- and eighth-order iteration methods by utilizing the idea of weight functions on the PotraPtak method for determining the approximate zeros of nonlinear models and applied them on some real-life engineering problems. The authors also analyzed the stability of the suggested schemes via basins of attraction for some cubic and quadratic polynomials.

The main contributions of the present research are given as follows:

(i) We developed and examined two novel predictor corrector type iterative techniques, namely, Algorithm 1 and Algorithm 2, in which Newton’s method is used in the predictor step.

(ii) We demonstrated that these newly created approaches have fourth- and sixth-order of convergence and are more efficient than the other well-known iterative methods of the same type.

(iii) The suggested approaches were used to solve several test cases in order to evaluate their validity and accuracy.

(iv) We compare the polynomiographs of newly proposed techniques to those of existing methods of the same category in terms of time and other dynamical aspects. The exhibited polynomiographs contain highly fascinating and attractive patterns that represent many polynomial characteristics.

The remaining sections of the paper are arranged as follows:

In Section 2, we have constructed two novel algorithms. The convergence criteria for the constructed algorithms have been discussed in Section 3. In Section 4, we solved different test problems for assuring the validity of the constructed methods. Section 5 includes the graphical properties of the constructed algorithms, and Section 6 contains the conclusion.

2. Construction of New Optimal Root-Finding Algorithms

By employing the technique of modified homotopy perturbation, Golbabai and Javidi [12] introduced the following iteration formula:

\[ x_{p+1} = x_p - \frac{\phi(x_p)}{\phi'(x_p)} \left[ \frac{\phi^2(x_p)}{2} \right] \]

which is a third-order iteration method, usually known as Javidi’s method. In [18], Rafiq and Raffullah considered Newton’s iteration method in the predictor step and presented a new two-step Javidi’s iteration method given as

\[ y_p = x_p - \frac{\phi(x_p)}{\phi'(x_p)} p = 0, 1, 2, \ldots, \]

\[ x_{p+1} = y_p - \frac{\phi'(y_p)}{\phi''(y_p)} \left[ \frac{\phi^2(y_p)}{2} \right] \]

To make it optimal, we consider the following approximations of first and second derivatives:

\[ \phi'(y_p) = \phi'(x_p), \]

\[ \phi''(y_p) = 4\phi'(x_p) + 10\phi(y_p) + 12, \]

\[ \eta(x_p, y_p). \]

Using the above approximations in (3), we gain new optimal root-finding algorithms having the following iterative form:

Algorithm 1: For a given \( x_0 \), compute the approximate solution \( x_{p+1} \) by the following iterative schemes:

\[ y_p = x_p - \frac{\phi(x_p)}{\phi'(x_p)} p = 0, 1, 2, \ldots, \]

\[ x_{p+1} = y_p - \frac{\phi'(y_p)}{\phi''(y_p)} \left[ \frac{\phi^2(y_p)}{2} \right] \]

which is fourth-order optimal root-finding algorithm for nonlinear scalar equations and it utilizes three functional evaluations per iteration. It should be noted that all the terms that appeared in the denominator of Algorithm 1 must not
be zero; otherwise, the method will fail to find the approximate solution to the given problem. To achieve better convergence, we utilize the same idea as described above and add one more step as Newton’s method which results in the following iterative method:

\[ y_p = x_p - \frac{\varphi(x_p)}{\varphi'(x_p)} \quad p = 0, 1, 2, \ldots, \]

\[ z_p = y_p - \frac{\varphi(y_p)}{\varphi'(y_p)} - \frac{\varphi''(y_p)\eta(x_p, y_p)}{2\varphi'(y_p)^2} \]

(6)

\[ x_{p+1} = z_p - \frac{\varphi(z_p)}{\varphi'(z_p)} \]

The above iteration scheme gains optimal order but does not fulfill the Kung and Traub’s conjecture [19]; to fulfill this conjecture, we consider the following approximations:

\[ \varphi'(z_p) = \frac{\varphi'(x_p)}{G(u_p, v_p, w_p)}, \]

where

\[ G = G(u_p, v_p, w_p), \]

\[ = 1 + 2u_p(1 + 3u_p + 3u_p^2) + v_p + 4w_p, \]

(8)

\[ u_p = \frac{\varphi(y_p)}{\varphi(x_p)}, \quad v_p = \frac{\varphi(z_p)}{\varphi(y_p)}, \quad w_p = \frac{\varphi(z_p)}{\varphi(x_p)}. \]

With the help of the above approximations in (6), we are able to suggest the following algorithm:

Algorithm 2. For a given \( x_0 \), compute the approximate solution \( x_{p+1} \) by the following iterative schemes:

\[ \phi(x_p) = \phi'(a)e_p + \frac{1}{2!}\phi''(a)e_p^2 + \frac{1}{3!}\phi'''(a)e_p^3 + \frac{1}{4!}\phi^{(4)}(a)e_p^4 + \frac{1}{5!}\phi^{(5)}(a)e_p^5 + \frac{1}{6!}\phi^{(vi)}(a)e_p^6 + O(e_p^7), \]

(10)

\[ \phi(x_p) = \phi'(a)[e_p + d_2e_p^2 + d_3e_p^3 + d_4e_p^4 + d_5e_p^5 + d_6e_p^6 + O(e_p^7)], \]

\[ \phi'(x_p) = \phi'(a)[1 + 2d_2e_p + 3d_2e_p^2 + 4d_3e_p^3 + 5d_4e_p^4 + 6d_5e_p^5 + 7d_6e_p^6 + O(e_p^7)], \]

(11)

where

\[ d_p = \frac{1}{p!}\frac{\phi^{(p)}(a)}{\phi'(a)} \]

With the help of (10) and (11), we get

\[ y_p = x_p - \frac{\phi(x_p)}{\phi'(x_p)}, \quad p = 0, 1, 2, \ldots, \]

\[ z_p = y_p - \frac{\phi(y_p)}{\phi'(y_p)} - \frac{\phi''(y_p)\eta(x_p, y_p)}{2\phi'(y_p)^2} \]

x_{p+1} = z_p - \frac{\phi(z_p)}{\phi'(z_p)}

which is a three-step optimal root-finding algorithm, having sixth convergence order and utilizing only four functional evaluations per iteration. One must keep in mind that all the terms that appeared in the denominator of Algorithm 2 must not be vanished at the initial guess in the given domain; otherwise, the method will not work properly to find the approximate solution of the given problem.

3. Convergence Analysis

This section of the paper contains the convergence analysis of the suggested iteration methods.

**Theorem 1.** Suppose \( \alpha \) be the actual root of equation \( \phi(x) = 0 \). If \( \phi(x) \) is differentiable near \( \alpha \), Algorithm 1 is of fourth-order convergence.

**Proof.** To prove the theorem, suppose \( \alpha \) be the exact root of the equation \( \phi(x) = 0 \) and \( e_p \) be \( p \)th-iteration’s error, where \( e_p = x_p - \alpha \), and with the help of Taylor’s series expansion around \( x = \alpha \), we obtain
fourth-order convergence.

4 Complexity

Using equations (10)–(15) in Algorithm 1, we obtain

\[ y_p = \phi'(\alpha) \left[ \alpha + d_2 e_p^2 + (2d_4 - 2d_2^2)e_p^3 + (3d_4 - 7d_2d_3 + 4d_2^2) e_p^4 + (-6d_2^2 + 20d_3d_5) e_p^5 \right. \\ -10d_2d_4 + 4d_3 - 8d_2^2 e_p^5 + \left. (-17d_4d_5 + 28d_2d_5^2 - 13d_2d_5 + 5d_6 + 33d_2d_5^2 - 52d_3d_5^2 \\
+16d_2^3) e_p^6 + O(e_p^7) \right]. \]

\[ \phi(y_p) = \phi'(\alpha) \left[ d_2 e_p^2 + (2d_4 - 2d_2^2)e_p^3 + (5d_4 - 7d_2d_3 + 4d_4)e_p^4 + \left[ -24d_3^2 + 12d_2d_5 \\
-10d_2d_4 + 4d_3 - 6d_2^2 e_p^5 + (-73d_4d_5 + 34d_2d_5^2 - 28d_2d_5^2 + 37d_4d_5^2 + 17d_4d_5 \\
13d_2d_5 + 5d_6) e_p^6 + O(e_p^7) \right]. \]

With the help of (10), (13), and (14), we get

\[ \eta(x_p, y_p) = \phi'\left(\alpha\right) \left[ 4e^{-1} + 22d_2 + \left( 40d_3 + 4d_2^2 \right) e_p + \left( 26d_2d_3 - 4d_2^3 + 58d_4 \right) e_p^2 \\
+ \left( 76d_2^2 + 44d_3d_5 + 36d_2^3 - 40d_3d_5^2 + 4d_2^3 \right) e_p^3 + \left( 94d_6 + 62d_2d_5 + 118d_4d_5 \right) \\
- \left( 58d_4d_5^2 - 102d_2d_5^3 + 64d_3d_5^3 - 4d_2^3 \right) e_p^4 + \left( 112d_2t + n80d_3d_5h_6, x1647d_5Cd_1 \right) \\
- \left( 76d_2d_5^2 + 96d_4d_5^2 + 72d_4d_5^3 + 252d_2d_5^3 - 108d_3d_5^4 - 288d_4d_5^4 - 76d_5^4 \right) \\
+ \left( 4d_2^5 \right) e_p^5 + \left( 130d_2 + 98d_2d_7 - 314d_4d_5^2 + 378d_3d_5^3 - 596d_2d_5^4 + 192d_2d_5^5 \\
- 200d_2d_5^4 + 266d_4d_5^4 - 76d_4d_5^3 + 90d_5d_5^3 - 94d_6d_2d_5^5 - 372d_5d_2d_5^5 + 596d_4d_5^5 \\
- 4d_2^710d_2d_5^6 \right) e_p^6 + O(e_p^7) \right]. \]

Using equations (10)–(15) in Algorithm 1, we obtain

\[ x_{p+1} = \alpha - \left( 8d_2^2 + d_2d_3 \right) e_p^4 + O(e_p^5), \] (16)

which implies that

\[ e_{p+1} = \alpha - \left( 8d_2^2 + d_2d_3 \right) e_p^4 + O(e_p^5). \] (17)

The above equations confirms that Algorithm 1 is of fourth-order convergence.

\[ \eta(x_p, y_p) = \phi'(\alpha) \left[ 2d_2 + (6d_2d_3 - 2d_2)e_p^2 + (12d_3^2 - 12d_2d_3 + 4d_2d_4 - 4d_2^3) e_p^3 + \left( 2d_2d_5 \\
- 26d_2d_4 - 42d_2d_3^2 + 24d_3d_5 + 2d_2d_5^2 \right) e_p^4 + \left( -48d_4d_5d_3 + 12d_2^3 - 24d_4d_5^2 \right) \\
+ 28d_3d_4 + 4d_3d_5^2 + 120d_3d_5^2 - 48d_3d_5^2 - 8d_4^2 - 36d_4^2 \right) e_p^5 + \left( -60d_2d_3d_5 + 28d_3d_5^2 \\
- 2d_2d_3^2 + 22d_3d_4 - 10d_3d_5 + 30d_4^2 + 6d_4^2 + 20d_2d_5^2 - 86d_4d_5^2 + 88d_4d_5^2 \\
+ 198d_2d_5^3 - 312d_2d_5^2 + 96d_5d_5^2 - 10d_5 \right) e_p^6 + O(e_p^7) \right]. \]

where \( G = G(u_p, v_p, w_p) \)

\[ = 1 + 2\mu_p \left( 1 + 3\mu_p + 3\mu_p^2 \right) + v_p + 4w_p, \]
\[ G(u_p, v_p, w_p) = \varphi'(\alpha) \left[ 1 + 2d_2 e_p + (3d_3 - 8d_2^2) e_p^3 + (-40d_2^3 - 32d_2 d_3 + 4d_4) e_p^5 + (5d_5 - 49d_3 d_2) \right. \\
\left. - 265d_3 d_2^2 + 33d_3^2 + 110d_1^3 e_p^6 + (6d_6 - 66d_3 d_2 - 102d_2 d_3 - 410d_2 d_3^2 - 590d_2 d_4^2) \right. \\
\left. + 552d_3 d_2^2 - 588d_2^2 e_p^6 + (-1831d_2^2 d_4 + 7d_7 - 83d_2^2 d_6) + 138d_2 d_6 - 556d_5 d_2^2 + 663d_2 d_4 + 615d_2 d_2^2 - 5023d_2 d_4^2 - 79d_2^2 - 441d_2^3 + 1421d_2^3 e_p^n + (-2486d_4 d_5) \right. \\
\left. + 784d_4 d_2 d_4 + 8d_4 - 100d_2 d_7 - 2058d_3 d_5^2 - 672d_2 d_5^2 - 18094d_2 d_5^3 + 11042d_2 d_5^4 \right. \\
\left. - 1422d_2 d_7^2 - 7286d_2 d_4^2 + 776d_2 d_4^2 - 702d_2 d_6^2 - 174d_2 d_6^2 - 5182d_2^3 e_p^n \right. \\
\left. + (-3863d_4 d_5 d_4 + 5330d_4 d_5^2 + 53693d_2 d_5^2 + 348d_2 d_5^2 + 3141d_2 d_5^2 + 9d_6 \right. \\
\left. - 117d_6 d_8 - 270d_4 d_4 - 320d_2 d_8^2 - 228d_4^2 d_4 - 14345d_4 d_4^2 - 2797d_2 d_4^2 - 9554d_2 d_4^4 \right. \\
\left. - 210d_2 d_8 - 848d_2 d_4^2 + 888d_2 d_4^2 - 35200d_2 d_4^2 + 28233d_2 d_4^2 - 58240d_2 d_4^2 - 145d_4^2 \right. \\
\left. - 1149d_4^2 + 14579d_4^2 e_p^n + O(e_p^n) \right] . \] 

Using equations (10)–(24) in Algorithm 2, we get

\[ x_{p+1} = \alpha + \left( -8d_3 d_2^2 - 64d_2^2 \right) e_p^n + O(e_p^n), \quad (25) \]

which implies that

\[ e_{p+1} = \alpha + \left( -8d_3 d_2^2 - 64d_2^2 \right) e_p^n + O(e_p^n). \quad (26) \]

The above equations confirm that Algorithm 2 is of sixth-order convergence.

4. Numerical Comparisons and Applications

To demonstrate the applicability and effectiveness of our newly devised iterative approaches, we present five real-world engineering problems and one very important and well-known nonlinear problem in this section. The devised iterative approaches are compared to the following existing two-step iterative algorithms:

4.1. Noor’s Method One (NM1). For the given initial guess \( x_0 \), calculate the approximate solution \( x_{p+1} \) using the iteration schemes as follows:

\[ x_{p+1} = x_p - \frac{\varphi(x_p)}{\varphi'(x_p)}, \quad p = 0, 1, 2, 3, \ldots, \]

\[ x_{p+1} = x_p - \frac{\varphi(x_p)}{\varphi'(x_p)} + \left[ \frac{\varphi(x_p)}{\varphi'(x_p)} \right] \frac{y_p}{\varphi'(x_p)}, \quad (27) \]

which is the second-order convergent method, known as Noor’s method one [11] for solving nonlinear scalar equations.

4.2. Chun’s Method (CM). For a given initial guess \( x_0 \), determine the approximate root \( x_{p+1} \) with the iteration schemes:

\[ y_p = x_p - \frac{\varphi(x_p)}{\varphi'(x_p)}, \quad p = 0, 1, 2, 3, \ldots, \]

\[ x_{p+1} = x_p - \frac{\varphi(x_p)}{\varphi'(x_p)} + \left[ 1 + \frac{\varphi(y_p)}{\varphi(x_p)} \right], \quad (28) \]

4.3. Chand’s Method (CHM). For the given initial guess \( x_0 \), calculate the approximate solution \( x_{p+1} \) using the iteration schemes:

\[ y_p = x_p - \frac{\varphi(x_p)}{\varphi'(x_p)}, \quad p = 0, 1, 2, 3, \ldots, \]

\[ x_{p+1} = x_p - \frac{\varphi(x_p) + \varphi(y_p)}{\varphi'(x_p)} + \left[ 1 + 2 \left( \frac{\varphi(y_p)}{\varphi(x_p)} \right)^2 \right], \quad (29) \]

which is the fourth-order two-step Chand’s method [16] for solving nonlinear scalar equations.

4.4. Noor’s Method Two (NM2). For the given initial guess \( x_0 \), calculate the approximate solution \( x_{p+1} \) using the iteration schemes:

\[ y_p = x_p - \frac{\varphi(x_p)}{\varphi'(x_p)}, \quad p = 0, 1, 2, 3, \ldots, \]

\[ z_p = -\frac{\varphi(x_p)}{\varphi'(x_p)}, \quad (30) \]

\[ x_{p+1} = x_p - \frac{\varphi(x_p) + \varphi(y_p + z_p)}{\varphi'(x_p)} + \left[ 1 + \frac{\varphi(y_p + z_p)}{\varphi(x_p)} \right], \]
which is three-step cubic-order Noor’s method two [13] for solving nonlinear scalar equations.

4.5. Yun’s Method (YM). For the given initial guess $x_0$, calculate the approximate solution $x_{p+1}$ using the iteration schemes:

$$y_p = x_p - \frac{\phi(x_p)}{\phi'(x_p)}, \quad p = 0, 1, 2, 3, \ldots,$$

$$z_p = -\frac{\phi(y_p)}{\phi'(x_p)},$$

$$x_{p+1} = x_p - \frac{\phi(x_p)}{\phi'(x_p)} + \frac{\phi(y_p)}{\phi'(x_p)} - \frac{\phi(z_p)}{\phi'(x_p)},$$

(31)

which is the three-step Yun’s method [21] for solving nonlinear scalar equations, having the convergence of fourth order. We evaluate the following test examples to conduct a numerical comparison of the above-described methods with our proposed algorithms:

Example 1. Kinetic problem equation.

The equation of kinetic problem has the following form:

$$e^{2100/T} = 1.11 \times 10^{11} T^2,$$

(32)

Where $T$ represents the temperature of the given system. (32) has been derived from the stirred reactor with the cooling coils [22]. By taking $T = x$, (32) may be rewritten in form of the following nonlinear function:

$$\phi_1(x) = x^{-2} e^{2100/x} - 1.11 \times 10^{11},$$

(33)

which can be used to find the temperature of the system. We start the iteration process with the initial guess $x_0 = 430$, and the related results from various iteration techniques are shown in Table 1.

Example 2. Planck’s radiation law.

The Planck’s radiation law [23] is used to compute the energy density within an isothermal black body with the standard form as

$$\phi(\sigma) = \frac{8 \pi cP}{\sigma^4 (e^{\frac{cP}{\Delta H} \sigma T} - 1)}.$$

(34)

Assume that we want to determine the wavelength sigma, that corresponds to maximal energy density $\phi(\sigma_1)$. We use $x = cP/\Delta H \sigma T$ to turn the aforementioned problem into a nonlinear equation, which has the following nonlinear equation:

$$1 - \frac{x}{5} = e^{-x},$$

(35)

which can be converted into the form of nonlinear function as follows:

$$\phi_2(x) = e^{-x} + \frac{x}{5} - 1.$$

(36)

The maximal wavelength of the radiation is represented by the estimated root of the aforementioned function $\phi_2$. To begin the iteration process, we take the starting guess $x_0 = 0.2$, and the relevant results from various iteration methods are shown in Table 2.

Example 3. Adiabatic flame temperature equation.

The equation of adiabatic flame temperature has the following form:

$$\phi_3(x) = \Delta H - a_1 (298 - x) - \frac{a_2}{2} (298^2 - x^2) - \frac{a_3}{3} (298^3 - x^3),$$

(37)

where we take $\Delta H = -57798, a_1 = 7.256, a_2 = 0.002298$, and $a_3 = 0.00000283$. For more information, one may see [24, 25] and the references are cited therein. The aforementioned function $\phi_3$ is actually a third-degree polynomial, and according to algebra’s fundamental theorem, it must have three unique roots (zeros) and $a = 430.30991366612556304019892945$ is a simple one among them that we estimated using the proposed algorithms with the starting guess $x_0 = 2000$, and the numerical results are presented in Table 3.

Example 4. Beam designing model.

We consider the problem of beam positioning from [26], which yields a nonlinear function as

$$\phi_4(x) = x^4 + 4x^3 - 24x^2 + 16x + 16.$$

(38)

The given function $\phi_4$ is actually a four-degree polynomial, and it must have precisely four roots (zeros) in the light of fundamental theorem of algebra. We choose the starting guess $x_0 = -0.75$ to approximate the required root using the proposed algorithms, and the numerical results are shown in Table 4.

Example 5. Open channel flow problem.

In fluid dynamics, Manning’s equation (27) deals with the water flow with the following standard form:

$$\text{water flow} = F = \frac{\sqrt{asr^{2/3}}}{N}.$$

(39)

In (39), the symbol $s$ stands for the slope, $a$ stands for the area, $r$ stands for the hydraulic radius, and $n$ stands for Manning’s roughness coefficient. For a channel with the rectangular-shape of width $w$ and depth $x$, we may have

$$a = wx, \quad & r = \frac{wx}{w + 2x}$$

(40)

Using these values in (39), we obtain

$$F = \frac{\sqrt{s}wx}{N} \left( \frac{wx}{w + 2x} \right)^{2/3}.$$

(41)

In order to compute water’s depth in a channel, we rewrite (41) in the following nonlinear form:
Table 1: Numerical comparison of various root-finding algorithms for the problem $\varphi_1$.

| Method     | $N$ | $x_{p1}$ | $|\varphi(x_{p1})|$ | $|x_{p1} - x_p|$ | CPU time |
|------------|-----|----------|---------------------|----------------|----------|
| NM1        | 12  | 551.7732493032699636215866007540 | 7.093691e−23 | 4.808708e−16 | 3.065    |
| CM         | 10  | 551.7732493032699636215866007312 | 1.837158e−18 | 9.899467e−07 | 3.128    |
| CHM        | 10  | 551.7732493032699636215866007540 | 2.258490e−46 | 1.218702e−13 | 3.190    |
| NM2        | 15  | 551.7732493032699636215866007540 | 2.913370e−27 | 3.081698e−18 | 3.253    |
| YM         | 10  | 551.7732493032699636215865875416 | 1.064742e−15 | 4.946704e−06 | 3.331    |
| Algorithm 1 | 9   | 551.7732493032699636215866007540 | 1.608420e−26 | 1.509462e−08 | 2.626    |
| Algorithm 2 | 8   | 551.7732493032699636215866007540 | 8.779657e−72 | 2.409901e−13 | 2.704    |

Table 2: Numerical comparison of various root-finding algorithms for the problem $\varphi_2$.

| Method     | $N$ | $x_{p1}$ | $|\varphi(x_{p1})|$ | $|x_{p1} - x_p|$ | CPU time |
|------------|-----|----------|---------------------|----------------|----------|
| NM1        | 5   | 0.00000000000000000000000003947489 | 3.157991e−24 | 2.513162e−12 | 3.521    |
| CM         | 3   | 0.00000000000000000000000000000000 | 1.571613e−40 | 1.158532e−10 | 3.600    |
| CHM        | 3   | 0.00000000000000000000000000000000 | 1.750456e−48 | 1.380631e−12 | 3.663    |
| NM2        | 5   | 0.0000000000000000000000000019832 | 1.586544e−26 | 1.781316e−13 | 3.707    |
| YM         | 3   | 0.00000000000000000000000000000000 | 2.329495e−42 | 4.155449e−11 | 3.403    |
| Algorithm 1 | 3   | 0.00000000000000000000000000000000 | 2.160782e−52 | 2.134128e−13 | 2.934    |
| Algorithm 2 | 2   | 0.0000000000000000000000000000232846266 | 1.862770e−22 | 1.814949e−04 | 2.986    |

Table 3: Numerical comparison of various root-finding algorithms for the problem $\varphi_3$.

| Method     | $N$ | $x_{p1}$ | $|\varphi(x_{p1})|$ | $|x_{p1} - x_p|$ | CPU time |
|------------|-----|----------|---------------------|----------------|----------|
| NM1        | 11  | 4305.309913666125563020922754179909 | 3.416939e−16 | 4.270236e−07 | 3.281    |
| CM         | 4   | 4305.30991366612556304098929464342 | 2.174776e−55 | 6.493737e−12 | 3.329    |
| CHM        | 3   | 4305.30991366612556304098929464342 | 5.855416e−30 | 1.704358e−05 | 3.391    |
| NM2        | 6   | 4305.30991366612556304099102978796 | 3.886295e−21 | 1.281244e−09 | 3.322    |
| YM         | 4   | 4305.30991366612556304098929464342 | 5.772631e−71 | 8.594129e−16 | 3.468    |
| Algorithm 1 | 4   | 4305.30991366612556304098928972873 | 1.060344e−23 | 1.332626e−05 | 2.516    |
| Algorithm 2 | 3   | 4305.309913666125563040116005825452 | 1.857091e−18 | 6.740210e−01 | 2.547    |

Table 4: Numerical comparison of various root-finding algorithms for the problem $\varphi_4$.

| Method     | $N$ | $x_{p1}$ | $|\varphi(x_{p1})|$ | $|x_{p1} - x_p|$ | CPU time |
|------------|-----|----------|---------------------|----------------|----------|
| NM1        | 4   | −0.535898384862245344805625149808 | 3.035870e−15 | 1.028354e−08 | 3.650    |
| CM         | 3   | −0.53589838486224512945107316988 | 4.071744e−45 | 2.889668e−12 | 3.712    |
| CHM        | 3   | −0.53589838486224512945107316988 | 1.103531e−48 | 4.228953e−13 | 3.743    |
| NM2        | 5   | −0.53589838486224512945107316988 | 2.255247e−29 | 8.863356e−16 | 3.808    |
| YM         | 3   | −0.53589838486224512945107316988 | 1.563471e−46 | 1.345709e−12 | 3.854    |
| Algorithm 1 | 3   | −0.53589838486224512945839237246 | 3.259623e−20 | 9.586839e−08 | 2.670    |
| Algorithm 2 | 2   | −0.53589838486224504466362113905 | 3.777599e−16 | 1.027830e−03 | 2.732    |

\[
\varphi_5(x) = \frac{\sqrt{\text{sum}}}{N} \left( \frac{wx}{w+2x} \right)^{2/3} - F. \tag{42}
\]

Example 6. A well-known nonlinear problem.

To analyze the proposed methods, we consider the following very important and well-known nonlinear problem:

\[
x = \tan x. \tag{43}
\]

The above equation in the form of nonlinear function $\varphi_6$ can be rewritten as

\[
\varphi_6(x) = x - \tan x. \tag{44}
\]
We start the iteration process with the initial guess $x_0 = 1.0$, and the related results from various iteration techniques are shown in Table 6.

The machine used for computing numerical results has the following specifications:

(i) 64 bit operating system
(ii) x64-based processor with Core(TM) m3-7Y30
   CPU@1.00 GHz 1.61GHz
(iii) 8 GB of memory

We use the accuracy $\varepsilon = 10^{-15}$ in the stopping criteria $|x_{p+1} - x_p| < \varepsilon$ for the all aforementioned problems. We used the computer application Maple 13 to compute all of the numerical results and can be observed in Tables 1–6.

Tables 1–6 represent the detailed comparison of the suggested root-finding methods with the other above-described methods for the engineering and arbitrary problems $\varphi_1, \varphi_2$. In the columns of the above-presented tables, N stands for the consumption of the iterations for different methods, $|\varphi(x)|$ stands for the modulus value of $\varphi(x)$, $x_{p+1}$ represents the final estimation, $|x_{p+1} - x_p|$ stands for the positive distance between the two consecutive estimations, and the last columns gives us the information about the CPU time consumption in seconds for different methods in comparison.

The careful examination of the obtained results in Tables 1–6 certifies that the proposed root-finding algorithms are showing better efficiency and performance which justified the supremacy of the suggested root-finding algorithms with respect to CPU-time consumption, accuracy, convergence-speed, no. of iterations, and computational order of convergence against the other comparable methods.

5. Dynamical Representation

In this section, we investigate the dynamical aspects of different algorithms with the aid of polynomiographs created through different algorithms for complex polynomials of different degrees. To generate polynomiographs of different complex polynomials by means of a computer program, we have to choose an initial rectangle $\mathcal{R}$ which contains the polynomial’s roots. Then, corresponding to each starting point $w_0$ in the region, we execute an iterative process and then colour the point corresponding to $w_0$ that relies on the approximate convergence of the truncated orbit to a root. The discretization of $\mathcal{R}$ is completely responsible for the image’s resolution quality. For instance, if we discretize $\mathcal{R}$ into a 2000 by 2000 grid, the output is a high-resolution picture.

We know that any complex polynomial $q$ having degree $n$ has exactly $n$-roots, and from the fundamental theorem of algebra, it may be uniquely defined as

$$q(w) = c_n w^n + c_{n-1} w^{n-1} + \cdots + c_1 w + c_0.$$  \(45\)

or by its zeros (roots) $\{w_1, w_2, \ldots, w_{n-1}, w_p\}$:

$$q(w) = (w - w_1)(w - w_2)\cdots(w - w_p).$$  \(46\)

where $\{c_n, c_{n-1}, \ldots, c_1, c_0\}$ are the complex coefficients.

The iterative algorithms can be easily applied to the both representations of the complex polynomial $q$. The polynomial’s degree depicts the number of basins of attraction. The location of basins can be managed by changing the position of roots in the complex plane manually. The polynomiographs’ colours depends upon the no. of iterations needed to attain the approximate solution of some polynomial with a given accuracy and a chosen scheme of iteration.

The main algorithm for drawing polynomiographs is given in Algorithm 3.

In Algorithm 3, the convergence test $(w_p + 1, w_p, \varepsilon)$ would be considered true in case of convergence and vice versa. The following is the standard form of the widely used convergence test:

$$|w_{p+1} - w_p| < \varepsilon.$$  \(47\)

In (47), $w_p$ and $w_{p+1}$ are the consecutive estimations in the iteration procedure, and the symbol $\varepsilon > 0$ stands for the accuracy. In this article, we also use the stopping criteria (47). We created visually appealing and intriguing polynomiographs using newly developed root-finding methods and compared them with the polynomiographs of the other similar methods. The colour of polynomiographs is determined by the no. of iterations required to estimate the roots of a polynomial with a certain precision $\varepsilon$. A huge number of similar graphics may be made by changing the value of the parameter $k$, where $k$ specifies the maximum no. of iterations. The work on polynomiography was first initiated by Kalantri [28–30] who described its artistic applications in different fields of science and arts. Gdawiec et al. [31, 32] put forward the work of Kalantri and presented fractal patterns of polynomial root-finding methods. Scott et al. [33], in 2011, worked on the basis of attraction for different existing methods and compared them with respect to their basis. In

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**Table 5: Numerical comparison among different algorithms for the problem $\varphi_k$.**

| Method      | $N$ | $x_{p+1}$ | $|\varphi(x_{p+1})|$ | $\sigma = |x_{p+1} - x_p|$ | CPU time |
|-------------|-----|-----------|-----------------------|-----------------------------|----------|
| $\varphi_1(x)$, $x_0 = 0.10$ |     | 1.46509122029582464237602073453 | 2.422027e−24 | 1.334423e−12 | 2.943 |
| CM          | 4   | 1.465091220295824642376021092486 | 2.481543e−24 | 2.175366e−06 | 3.391 |
| CHM         | 4   | 1.46509122029582464237602459842 | 4.889610e−23 | 4.918775e−06 | 3.468 |
| NM2         | 6   | 1.465091220295824642383819255359 | 1.059172e−19 | 2.790353e−10 | 3.431 |
| YM          | 4   | 1.46509122029582464237602099779 | 4.475999e−35 | 5.351749e−09 | 3.593 |
| Algorithm 1 | 4   | 1.46509122029582464237602099825 | 6.277761e−28 | 3.483992e−07 | 2.826 |
| Algorithm 2 | 3   | 1.46509122029582464237602099779 | 8.454782e−89 | 5.011500e−15 | 2.920 |
In this sense, the polynomiography gives us a new way to analyze the graphical behaviors of different existing methods in the literature.

We investigate the following complex polynomials for the aim of generating polynomiographs using the suggested methods, and we compare them with other well-known two-step iteration methods.

\[ q_1(w) = w^3 - 1, \quad q_2(w) = w^3 - w.i - 1, \quad q_3(w), \]

\[ q_4(w) = w^3 + w^2 + w + 1, \quad q_5(w) = w^3.i - w^2 + i. \]

The colormap that has been used for the coloring of iterations in the generation of polynomiographs is presented in Figure 1:

Example 7. Polynomiographs corresponding to polynomial \( q_1(w) \) through various numerical algorithms.

In this example, we investigate and compare the dynamical results obtained through different iteration schemes with our presented algorithms by considering the cubic polynomial \( w^3 - 1 \) which possesses three distinct simple zeros: \( 1, -1/2 - \sqrt{3}/2i, \) and \(-1/2 + \sqrt{3}/2i\). We executed all the algorithms to achieve the simple zeros of the considered polynomials, and the results can be visualized in Figures 2–8.

Example 8. Polynomiographs corresponding to polynomial \( q_2(w) \) through various numerical algorithms.

This example includes the dynamical comparison of the suggested iteration schemes with different similar-nature iterative algorithms by taking the cubic complex polynomial \( w^3 - w.i - 1 \). The degree of this complex polynomial is three, and according to the fundamental theorem of algebra, it has exactly three roots which are all simple and given as \( (1/6)[4 + (4i/9)\sqrt{81 + 12i}]^{1/3} + 4i/4 + (4i/9)\sqrt{81 + 12i}^{1/3}, \)

\( (1/12)[3i(4 + (4i/9)\sqrt{81 + 12i}]^{2/3} + 4i/4 + (4i/9)\sqrt{81 + 12i}]^{1/3}, \) and \( (1/12)[3i(4 + (4i/9)\sqrt{81 + 12i}]^{2/3} - 4i/4 + (4i/9)\sqrt{81 + 12i}]^{1/3}. \) Using computer program, we executed all the iteration processes, and the corresponding results can be seen in Figures 9–15.

Example 9. Polynomiographs corresponding to polynomial \( q_3(w) \) through various numerical algorithms.

We consider the complex polynomial \( w^3 + w.i - 1 \) in this example for analyzing the behaviors of different iteration schemes graphically. For this purpose, we generated the polynomiographs of the considered polynomials whose simple zeros are \( (1/6)[4 + (4i/9)\sqrt{81 + 12i}]^{1/3} + 4i/4 + (4i/9)\sqrt{81 + 12i}^{1/3}, \)

\( (1/12)[3i(4 + (4i/9)\sqrt{81 + 12i}]^{2/3} + 4i/4 + (4i/9)\sqrt{81 + 12i}]^{1/3}, \) and \( (1/12)[3i(4 + (4i/9)\sqrt{81 + 12i}]^{2/3} - 4i/4 + (4i/9)\sqrt{81 + 12i}]^{1/3}. \)

The colormap that has been used for the coloring of iterations in the generation of polynomiographs is presented in Table 1:

| Method | \( N \) | \( x_{p1} \) | \( |\psi(x_{p1})| \) | \( \sigma = |x_{p1} - x_p| \) | CPU time |
|--------|--------|-------------|----------------|-----------------|---------|
| NM1    | 15     | 0.0000260887664699846588865903 | 5.918878e-15 | 2.809559e-05 | 2.728   |
| CM     | 16     | 0.000028182936395409818132474046 | 7.461695e-15 | 2.714568e-05 | 2.791   |
| CHM    | 16     | 0.000016015226087560491752529952 | 1.369235e-15 | 1.653393e-05 | 2.822   |
| NM2    | 22     | 0.00002182070318494586097939226 | 3.463259e-15 | 1.420995e-05 | 2.460   |
| YM     | 16     | 0.00002655497860302085030134645 | 6.241897e-15 | 2.583725e-05 | 2.907   |
| Algorithm 1 | 15 | 0.0000187707752872094881266085980 | 2.204578e-15 | 2.149290e-05 | 2.600   |
| Algorithm 2 | 8  | 0.0000181998895819807055092293023 | 2.009489e-15 | 6.032757e-05 | 2.663   |

Complexity

Example 10. Polynomiographs corresponding to polynomial \( q_4(w) \) through various numerical algorithms.

In this example, we show the dynamics of different iteration schemes in the form of polynomiographs by taking the complex polynomial \( w^3 + w^2 + w + 1 \), whose simple zeros are \( 1, i, \) and \(-i\) that can be visualized easily on the complex planes of the corresponding polynomiographs that are shown in Figures 23–29.

Example 11. Polynomiographs corresponding to polynomial \( q_5(w) \) through various numerical algorithms.

In the eleventh example, we take the polynomial \( w^3 + w^2 + w + 1 \), having simple zeros \(-1, i, \) and \(-i\). To draw the polynomiographs, we executed all the iteration schemes with the help of computer program, and the corresponding graphical objects can be visualized in Figures 30–36.

Example 12. Polynomiographs corresponding to polynomial \( q_6(w) \) through various numerical algorithms.

In the last and final experiment, we show the graphical representations of different iteration schemes by generating
Figure 1: The colormap used for generating polynomiographs.

Figure 2: Polynomiograph for $q_1(w)$ using NM1.

Figure 3: Polynomiograph for $q_1(w)$ using CM.

Figure 4: Polynomiograph for $q_1(w)$ using CHM.

Figure 5: Polynomiograph for $q_1(w)$ using NM2.

Figure 6: Polynomiograph for $q_1(w)$ using YM.

Figure 7: Polynomiograph for $q_1(w)$ using Algorithm 1.
the polynomiographs of the complex polynomial $w^3 - w^2 + i$ whose simple zeros are $[-108 + 8i + 12\sqrt{81-12i}]^{2/3}$, $[12\sqrt{81-12i}]^{1/3}$, $rac{3}{6}[-108 + 8i + 12\sqrt{81-12i}]^{1/3}$, and $[-108 + 8i + 12\sqrt{81-12i}]^{1/3}$.
For this purpose, we ran all the iteration schemes with the aid of computer program and the corresponding graphs can be seen in Figures 37–43. In all six experiments, we considered the different cubic complex polynomials for examining the graphical aspects of the suggested iteration schemes. In all the obtained images, the regions of convergence for the suggested iteration schemes possess the larger convergence areas than the other.
comparable methods which certified the efficiency and better convergence of our proposed algorithms. The colour tones represent the performance and efficiency of the considered algorithm used to build the polynomiograph. The two important aspects which can be exhibited by these graphical objects are the convergence-speed and the dynamics of the
considered iteration techniques used to build these graphs. The first may be shown by examining the image’s colour tones. The darkness of the colours in the presented images demonstrates fast convergence with less number of iterations, i.e., the darker the image, the more efficient the approach, and the given images demonstrate the superiority of
the suggested methods. The second aspect may be examined by observing the colour fluctuation of the drawn polynomiographs. The regions with a limited variety of colours have low dynamics, whereas the regions with a great diversity of colours have high dynamics. The black colour in the displayed graphical representations demonstrates the
method’s deficiency by locating those precise locations where the solution cannot be obtained for the specified no. of iterations with the defined precision. The same-coloured regions in the figures show the same amount of iterations spent by different iteration strategies to approximate the answer and provide a comparable perspective of the contour.
lines on the map. All of the graphics were created using the computer program Mathematica 12.0 with the accuracy \( \epsilon = 0.01 \), and the upper bound of the no. of iterations \( m = 15 \).

6. Conclusions

In this study, we have established and analyzed two novel optimal root-finding algorithms for nonlinear functions. The convergence criterion of the presented algorithms has been discussed and verified that the suggested iterative algorithms bear fourth- and sixth-order convergence. To exhibit the applicability of the suggested algorithms, some real-life engineering applications have also been added and solved whose numerical results confirmed that the proposed algorithms are time-efficient and consumed less iterations to achieve the required solution and more accurate to the exact solution. The dynamics of the provided methods demonstrating the greater convergence area in comparison with the other comparable methods. These dynamics also highlighted the proposed algorithms’ quicker convergence speed and other dynamical properties, proving their superiority over the others in comparison.

Data Availability

All data required for this paper are included within this paper.

Conflicts of Interest

The authors do not have any conflicts of interest.

Authors’ Contributions

All authors contributed equally in this paper.

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