

Bézier curve technique for solving p -fractional differential equations

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Abstract

The Bézier curve technique is a numerical method often adopted for solving complex differential equations, including fractional differential equations. The quantum analogue of fractional differential equations extends classical fractional differential equations into the quantum domain, involving fractional calculus within quantum mechanical frameworks. In this study, the stated Liouville-Caputo type p -fractional differential equation (pFDE) is solved by utilizing the Bézier curve method. Firstly, the p -fractional differential equation is transformed into the equivalent system of weakly singular p -integral equations by using several results of fractional p -calculus. Secondly, the Bézier curve method is used to solve the latter system of weakly singular p -integral equations. The stated method is an approximation technique that produces highly accurate results with minimal errors. Numerical examples are also given to check the validity of the BCM technique.

Keywords. p -fractional differential equation, Bézier curve, p -fractional derivative, Simulation.

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1. INTRODUCTIONS AND MOTIVATIONS

Fractional modeling has become widely used in different sciences during the past three decades or more. In addition, many physical and engineering topics have attracted much attention from researchers (see [7, 8, 17, 23]). The fractional calculus (FC) generalize the operations of differentiation and integration to non-integer orders. FC emerged as a main tool for the study of dynamical systems, since fractional order operators are non-local and capture the history of dynamics. The p -fractional calculus is the Liouville-Caputo type p -fractional calculus (pFC). In stochastic analysis fields and quantum mechanics, we can find the p -fractional calculus. The Liouville-Caputo type p -fractional calculus is one of the classical p -fractional calculus. Some scientists have studied the existence of solutions for the Liouville-Caputo type p -fractional boundary value problems (see [2, 4, 6, 9, 16, 18]).

Jarad et al.[19] studied the stability of Liouville-Caputo type p -fractional non-autonomous systems by using Lyapunov's direct technique.

On the numerical methods, some techniques were presented to achieve an approximate solution of the pFDE [1]. Then, the convergence of these techniques was analyzed (see [22]). In [26], the finite difference method was used to solve the Liouville-Caputo type pFDE. The variational iteration technique and the Lagrange multipliers technique have been used to study the Liouville-Caputo type pFDE (see [24]). For this problem, the utilization of the Bézier curve method (BCM) [10] is a new idea. Also this approach is simple to use. Therefore, we consider BCM for this problem. Additionally many researchers have utilized the BCM: For example, the numerical solution a delay differential equation (DDE) obtained using [13] and [14], and some examples for linear optimal control systems with pantograph delays have been solved by BCM [15]. Although the use of this method is very straightforward and simple (see the results). For the collocation technique, one can refer to [3, 5, 20].

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In this paper, the approximate solution of IVPCpF via BCM is presented. The lemma is presented for the truncated error. Also, some numerical examples are presented to verify our technique.

The organization of the paper is organized as follows: Section 1 describes the introduction and motivation of the basic idea. Basic preliminaries are presented in Section 2. The Bézier curve method is introduced in Section 4. The application of the current method is simulated in Section 5. The last Section 6 is dedicated to a concluding remark on concluding remarks.

2. BASIC PRELIMINARIES

Definition 2.1. (see [11]) Let $p \in (0, 1]$ and

$$[t]_p = \frac{1 - p^t}{1 - p}, \quad t \in \mathbb{R},$$

where $\mathbb{R}$ is the set of real numbers. The p -analogue of the power function $(t - s)^n$ with $n \in \mathbb{N}_0 = \mathbb{N} \cup \{0\}$ is

$$(t - s)^0 = 1, \quad (t - s)^n = \prod_{i=0}^{n-1} (t - p^i s), \quad n \in \mathbb{N}, \quad t, s \in \mathbb{R},$$

where $\mathbb{N}$ is the set of natural numbers. For $0 \leq s \leq t$, we have

$$(t - s)^{(\beta)} = t^\beta \prod_{i=0}^{\infty} \frac{t - p^i s}{t - p^{\beta+i} s}, \quad (2.1)$$

where $\beta > 0$ and $0 < |p| < 1$. Note that, if $s = 0$ then $t^{(\beta)} = t^\beta$. For $t_0 \leq t_1 \leq t$, we have

$$(t - t_0)^{(\beta)} \geq (t - t_1)^{(\beta)},$$

where $0 < |p| < 1$, $\beta \in \mathbb{C} \setminus \{-n : n \in \mathbb{N} \cup \{0\}\}$, $\mathbb{C}$ is the set of complex number, and $\mathbb{N} = \{1, 2, 3, \dots\}$, then

$$\begin{aligned} \Gamma_p(\beta) &= (1 - p)^{1-\beta} (1 - p)^{(\beta-1)}, \\ \Gamma_p(\beta + 1) &= [\beta] \Gamma_p(\beta), \quad \Gamma_p(1) = 1, \end{aligned}$$

where $[\beta] = (1 - p^\beta) / (1 - p)$.

Definition 2.2. (see [18]) If g is a real or complex valued function, $t \in A$ (on p geometry set A , where $p \in R$ be an invariant point, a subset A of C is called p geometric if $pt \in A$ whenever $t \in A$), $|p| \neq 1$, then

$$\begin{aligned} D_p g(t) &= \frac{d_p}{d_p t} g(t) = \frac{g(pt) - g(t)}{(p - 1)t}, \quad t \in A \setminus 0, \\ D_p g(0) &= \frac{d_p}{d_p t} g(t) \Big|_{t=0} = \lim_{n \rightarrow \infty} \frac{g(t^n) - g(0)}{tp^n}, \quad |p| < 1. \end{aligned}$$

Definition 2.3. (see [25]) Let $t \in A$ (p -geometry set A), $\beta \neq -1, -2, \dots$ and $\beta \geq 0$. The β -order p -fractional integral of the Riemann-Liouville type with the lower limit point a is can be defined as $I_{p,a} g(t) = g(t)$,

$$I_{p,a}^\beta g(t) = \frac{1}{\Gamma_p(\beta)} \int_a^t (t - ps)^{\beta-1} g(s) d_p s.$$

Definition 2.4. (see [25]) Let $a \in T_p$, where $T_p = \{p^n : 0 < p < 1, n \in \mathbb{Z} \cup \{0\}\}$, $\mathbb{Z} = \{0, +1, -1, +2, -2, \dots\}$. The β -order Riemann-Liouville type p -fractional derivative (FD) of a function $g(t) : (a, \infty) \rightarrow R$ can be defined as

$$(D_{p,a}^\beta g)(t) = \begin{cases} (I_{p,a}^{-\beta} g)(t), & \beta \leq 0, \\ \left(D_{p,a}^{[\beta]} I_{p,a}^{[\beta]1-\beta} g \right)(t), & \beta > 0, \end{cases}$$

where $[\beta]$ be the smallest integer that is greater than or equal to β .



Definition 2.5. (see [25]) Let $a \in T_p$. The β -order Liouville-Caputo type p -FD of a function $g(t) : (a, \infty) \rightarrow R$ can be defined as

$$({}^c D_{p,a}^\beta g)(t) = \begin{cases} (I_{p,a}^{-\beta} g)(t), & \beta \leq 0, \\ (I_{p,a}^{[\beta]-\beta} D_{p,a}^{[\beta]} g)(t), & \beta > 0. \end{cases}$$

For convenience, we use the notations $I_p^\beta g(t)$, $D_p^\beta g(t)$, and ${}^c D_p^\beta g(t)$ instead of $I_{p,0}^\beta g(t)$, $D_{p,0}^\beta g(t)$, and ${}^c D_{p,0}^\beta g(t)$ respectively.

Definition 2.6. (see [26]) A function g defined on $[0, b]$ is called p -absolutely continuous if g is continuous and for $t \in (pb, b]$, there exists a constant $M > 0$, where

$$\sum_{j=0}^{\infty} |g(tp^j) - g(tp^{j+1})| \leq M.$$

Introduce the space $\mathcal{AC}_p^{(n)}[0, b] = \{D_p^{k-1}g \in \mathcal{AC}_p[0, b], k = 1, 2, \dots, n\}$, where $\mathcal{AC}_p[0, b]$ is composed of all functions which are p -absolutely continuous on $[0, b]$.

Definition 2.7. Let $g(t)$ on (t_0, t_1) be a real valued function on a set A . The p -integral can be defined as

$$\int_{t_0}^{t_1} g(t) d_p t = \int_0^{t_1} g(t) d_p t - \int_0^{t_0} g(t) d_p t,$$

where

$$\int_0^x g(t) d_p t = (1-p) \sum_{n=0}^{\infty} x p^n g(x p^n), \quad x \in A.$$

Also

$$\int_0^1 t d_p t = \frac{1}{1+p}, \quad \text{and} \quad \int_0^1 t^n d_p t = \frac{p-1}{p^{n+1}-1}.$$

Definition 2.8. (see [9]) If $\beta > 0$, $n = [\beta]$, $t \in (0, b]$, $g \in \mathcal{AC}_p^{(n)}[0, b]$ and $D_p^n g \in C[0, b]$, then

$${}^c D_p^\beta g(t) = D_p^\beta \left(g(t) - \sum_{j=0}^{n-1} \frac{D_p^j g(0)}{\Gamma_p(j+1)} t^j \right).$$

3. THE APPROXIMATION METHOD

The initial value problem of the β -order ($0 < \beta < 1$) Liouville-Caputo type p -fractional (IVPCpF) differential equation ($0 < p < 1$) can be introduced by

$$\begin{aligned} {}^c D_p^\beta z(t) &= g(t, z(t)), \quad 0 \leq t \leq 1, \\ z(t_0) &= z_0, \quad t_0 \in T_p, \quad t_0 = 0, \end{aligned} \tag{3.1}$$

where $g : T_p \times R^n \rightarrow R^n$ is continuous function, the time scale $T_p = \{p^n : n \in \mathbb{Z}\} \cup \{0\}$, $\mathbb{Z}$ is the set of integers, and t denotes time here.

Now, a difference formula is constructed to discretize the pCF,

$${}^c D_p^\beta z(t) = D_p^\beta z(t) - \frac{z(0)}{\Gamma_p(1-\beta)} t^{-\beta}.$$

Let $0 = t_0 < t_1 < \dots < t_N = 1 \in T_p$ be a nonuniform partition of $[0, 1]$, $t_k = p^{N-k}$ ($1 \leq k \leq N$), $\Delta t_1 = p^{N-1}$, $\Delta t_k = p^{N-k} - p^{N-k+1}$ ($2 \leq k \leq N$), where $N \geq 1$, $N \in \mathbb{Z}^+$, $g(t, s) = (t - ps)^{(-\beta)} z(s)$, $g(pt, t) = 0$,



therefore one may have

$$\begin{aligned} {}^c D_p^\beta z(t_n) &= D_p I_p^{1-\beta} z(t_n) - \frac{z(0)}{\Gamma_p(1-\beta)} t_n^{-\beta} \\ &= D_p \frac{1}{\Gamma_p(1-\beta)} \int_0^{t_n} (t_n - ps)^{(-\beta)} z(s) d_p s - \frac{z(0)}{\Gamma_p(1-\beta)} t_n^{-\beta} \\ &= \frac{1}{\Gamma_p(1-\beta)} \int_0^{t_n} D_p (t_n - ps)^{(-\beta)} z(s) d_p s - \frac{z(0)}{\Gamma_p(1-\beta)} t_n^{-\beta}, \end{aligned}$$

then

$$\begin{aligned} {}^c D_p^\beta z(t_n) &= \frac{1}{\Gamma_p(-\beta)} \int_0^{t_n} (t_n - ps)^{(-\beta-1)} z(s) d_p s - \frac{z(0)}{\Gamma_p(1-\beta)} t_n^{-\beta} \\ &= \frac{1}{\Gamma_p(-\beta)} \sum_{k=1}^n \int_{t_{k-1}}^{t_k} (t_n - p)^{(-\beta-1)} z(s) d_p s - \frac{z(0)}{\Gamma_p(1-\beta)} t_n^{-\beta}. \end{aligned} \quad (3.2)$$

For discretizing the integral in (3.2), one may have

$$L_{1,k}(s) = \frac{s - t_{k-1}}{\Delta t_k} z(t_k) + \frac{t_k - s}{\Delta t_k} z(t_{k-1}), \quad s \in [t_{k-1}, t_k], k = 1, 2, \dots, N.$$

Theorem 3.1. Assume that $0 < \beta, p < 1$, $z(t)$ be a continuous function on $[0, 1]$, $M_1 = \sup_{0 \leq t \leq 1} |D_p^2 z(t)|$, then for any fixed δ ($0 < \delta < 1$, t_n ($n \leq (1 - \delta)N$)) the truncation error $r(t_n)$ can be written by:

$$|r(t_n)| < \frac{M_1(1-p)^2 p^{(2-\beta)\delta N}}{4(1-p^\beta)(1-p^{1-\beta})|\Gamma_p(-\beta)|}.$$

Proof. See [26]. □

4. THE BÉZIER CURVE METHOD

Let k be a chosen positive integer and $\{t_0 \leq t_1 \leq \dots \leq t_k = t_f\}$ be a partition of $[t_0, t_f]$. The idea is to utilize BCM to approximate the solution $z(t)$. Define the Bézier polynomials of degree n over the interval $[t_{j-1}, t_j]$ as follows:

$$z_j(t) = \sum_{r=0}^n w_r^j B_{r,n} \left(\frac{t - t_{j-1}}{h} \right), \quad (4.1)$$

where $h = t_j - t_{j-1}$, and

$$B_{r,n} \left(\frac{t - t_{j-1}}{h} \right) := \binom{n}{r} \frac{1}{h^n} (t_j - t)^{n-r} (t - t_{j-1})^r,$$

is the Bernstein polynomial of degree n over $[t_{j-1}, t_j]$, and w_r^j are unknown control points. Also, one may have

$$C^T = \langle z_j(t), \phi(t) \rangle Q_n^{-1},$$

$$C = [c_0 \quad c_1 \quad \dots \quad c_n].$$

For $\Omega = [t_{j-1}, t_j]$, and $T_n(t) = [1 \quad t \quad \dots \quad t^n]^T$, we have

$$\begin{aligned} \phi(t) &= \langle B_{0,n}(t), \dots, B_{0,n}(t) \rangle, \\ \langle z_j(t), \phi(t) \rangle &= \int_{\Omega} z_j(t) \phi^T(t) dt \\ &= [\langle z_j(t), B_{0,n}(t) \rangle \quad \langle z_j(t), B_{1,n}(t) \rangle \quad \dots \quad \langle z_j(t), B_{n,n}(t) \rangle], \end{aligned}$$



where the $(n+1) \times (n+1)$ matrix Q_n are considered as

$$\begin{aligned} Q_n &= \langle \phi(t), \phi(t) \rangle = \int_{\Omega} \phi(t) \phi^T(t) dt \\ &= \int_{\Omega} (\psi_n^{\Omega} T_n(t)) (\psi_n^{\Omega} T_n(t))^T dt \\ &= \psi_n^{\Omega} \int_{\Omega} T_n(t) (T_n(t))^T dt (\psi_n^{\Omega})^T = \psi_n^T G_{\Omega, n} (\psi_n^{\Omega})^T, \end{aligned}$$

and

$$G_{\Omega, n} = \begin{bmatrix} (t_j - t_{j-1}) & \frac{(t_j^2 - t_{j-1}^2)}{2} & \cdots & \frac{(t_j^{n+1} - t_{j-1}^{n+1})}{n+1} \\ \frac{(t_j^2 - t_{j-1}^2)}{2} & \frac{(t_j^3 - t_{j-1}^3)}{3} & \cdots & \frac{(t_j^{n+2} - t_{j-1}^{n+2})}{n+2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{(t_j^{n+1} - t_{j-1}^{n+1})}{n+1} & \frac{(t_j^{n+2} - t_{j-1}^{n+2})}{n+2} & \cdots & \frac{(t_j^{2n+1} - t_{j-1}^{2n+1})}{2n+1} \end{bmatrix},$$

and ψ_n^{Ω} is the $(n+1)(n+1)$ matrix, where

$$\begin{aligned} \psi_n^{\Omega} &= \psi^{n+1} A^{n+1}, \\ \psi^{n+1}(i+1, j+1) &= \begin{cases} \frac{(-1)^{j-i}}{h^j} \binom{n}{i} \binom{n-i}{j-i}, & i \leq j, \\ 0, & j > i, \end{cases} \end{aligned}$$

and for $i, j = 0, 1, \dots, n$, we have

$$A^{n+1}(i+1, j+1) = \begin{cases} \binom{i}{j} (-a)^{i-j}, & j \leq i, \\ 0, & j > i. \end{cases}$$

Lemma 4.1. *Let the function $z_{\text{exact}} : [t_{j-1}, t_j] \rightarrow R$ be $n+1$ times continuously differentiable, $z_{\text{exact}} \in C^{m+1}[t_{j-1}, t_j]$ and $Y = \text{Span}\{\psi_{i,m} \mid i = 0, 1, \dots, n, m = 0, 1, \dots, k-1\}$, if $C^T \phi$ is the best approximation to z_{exact} in Y , then we have*

$$\begin{aligned} \|z_{\text{exact}} - C^T \phi\|_2 &\leq \frac{M}{(n+1)! k^{n+1} \sqrt{3n+3}}, \\ M &= \max_{t \in [t_{j-1}, t_j]} |z_{\text{exact}}^{(n+1)}(t)|. \end{aligned}$$

Proof. Suppose that the Taylor polynomial of order n for the function $z_{\text{exact}} = g_{\text{exact}}$ on $\left[\frac{m}{k}, \frac{m+1}{k}\right)$ as

$$y_m(t) = g_{\text{exact}}\left(\frac{m}{k}\right) + g'_{\text{exact}}\left(\frac{m}{k}\right)\left(t - \frac{m}{k}\right) + \dots + g^{(n)}_{\text{exact}}\left(\frac{m}{k}\right) \frac{\left(t - \frac{m}{k}\right)^n}{n!},$$

$m = 0, 1, \dots, k-1$, we can compute

$$|g(t) - y_n(t)| \leq \|g^{(n+1)}(\eta)\| \frac{\left(t - \frac{m}{k}\right)^{n+1}}{(n+1)!}, \quad \eta \in \left[\frac{m}{k}, \frac{m+1}{k}\right),$$



then, we have

$$\begin{aligned}
 \|g - C^T \phi\|_2^2 &= \int_{[t_{j-1}, t_j]} |g(t) - C^T \phi(t)|^2 dt \\
 &= \sum_{m=1}^{k-1} \int_{[\frac{m}{k}, \frac{m+1}{k}]} |g(t) - C^T \phi(t)|^2 dt \\
 &\leq \sum_{m=1}^{k-1} \int_{\frac{m}{k}}^{\frac{m+1}{k}} |g(t) - y_m(t)|^2 dt \\
 &\leq \sum_{m=1}^{k-1} \int_{[\frac{m}{k}, \frac{m+1}{k}]} \left[g^{(n+1)}(\eta) \frac{(t - \frac{m}{k})^{n+1}}{(n+1)!} \right]^2 dt \\
 &\leq \frac{M^2}{(n+1)!^2} \sum_{m=0}^{k-1} \int_{[\frac{m}{k}, \frac{m+1}{k}]} \left(t - \frac{m}{k} \right)^{2n+2} dt \\
 &= \frac{M^2}{[(n+1)!]^2 k^{2n+2} (2n+3)}.
 \end{aligned}$$

Now, the proof is completed. $\square$

Note: Also, we have

$$\begin{aligned}
 \frac{dB_{r,n}(\tau)}{d\tau} &= n(B_{r-1,n-1}(\tau) - B_{r,n-1}(\tau)), \\
 \frac{dz_j(\tau)}{d\tau} &= \sum_{r=0}^{n-1} n w_r^j B_{r-1,n-1}(\tau) - \sum_{r=0}^{n-1} n w_r^j B_{r,n-1}(\tau) \\
 &= \sum_{r=0}^{n-1} n w_{r+1}^j B_{r,n-1}(\tau) - \sum_{r=0}^{n-1} n w_r^j B_{r,n-1}(\tau) \\
 &= \sum_{r=0}^{n-1} B_{r,n-1}(\tau) n (w_{r+1}^j - w_r^j).
 \end{aligned}$$

By substituting $z_j(t)$, Eqs. (3.1) and (4.1), one may obtain a simplified problem. This problem can be solved by Maple 16. The convergence of this method is similar to the method in [15]. In [12], for

$$\begin{aligned}
 {}^c D_p^\beta z_i(t) &= f_i(t, z_1, z_2, \dots, z_n), \quad t_0 \leq t \leq 1, i = 1, 2, \dots, n, \\
 D_p^j z_i(t_0) &= b_{ij}, \quad b_{ij} \in R, \quad i = 1, \dots, n, \quad j = 0, 1, \dots, [\beta] - 1,
 \end{aligned}$$

we have

$$z_i(t) = \sum_{j=0}^{[\beta]-1} \frac{b_{ij}}{\Gamma_p(j+1)} t^j + \frac{(1-p)}{\Gamma_p(\beta)} \sum_{k=0}^{\infty} t p^k \left(t - t p^{(k+1)} \right)^{(\beta-1)} f_i(t p^k, z_1(t p^k), \dots, z_n(t p^k)) d_p s,$$

be done in the following step

- Degree raising case of the Bézier polynomial approximation.

Remark 4.2. Consider the following system:

$$\begin{aligned}
 {}^c D_p^\beta z(t) &= g(t, z(t)) = A(t)z(t) + F(t), \quad 0 \leq t \leq 1, \\
 z(t_0) &= z_0.
 \end{aligned} \tag{4.2}$$

Sufficient conditions for the existence and uniqueness of the solution of the pantograph delay differential Equation (4.2) are



- the $z(t)$ is continuous;
- the right-hand side of (4.2) satisfies Lipschitz condition;
- the right-hand side of (4.2) is bounded.

4.1. **The convergence of the approximate solution.** One may consider the following problem:

$$\begin{aligned} I(z(t), {}^c D_p^\beta z(t)) &= {}^c D_p^\beta z(t) - A(t)z(t) = F(t), \quad 0 \leq t \leq 1, \\ z(t_0) &= z_0 = a \in \mathbb{R}. \end{aligned} \quad (4.3)$$

Lemma 4.3. For a polynomial in Bézier form

$$z(t) = \sum_{i=0}^{n_1} c_{i,n_1} B_{i,n_1}(t),$$

then we have

$$\frac{\sum_{i=0}^{n_1} c_{i,n_1}^2}{n_1 + 1} \geq \frac{\sum_{i=0}^{n_1+1} c_{i,n_1+1}^2}{n_1 + 2} \geq \dots \geq \frac{\sum_{i=0}^{n_1+m_1} c_{i,n_1+m_1}^2}{n_1 + m_1 + 1},$$

where c_{i,n_1+m_1} is the Bézier coefficients of $z(t)$ after it is degree-elevated to degree $n_1 + m_1$.

Proof. See [27]. □

Theorem 4.4. If the problem (4.3) has a unique C^1 continuous solution $\bar{z}$, then the approximate solution obtained by the control-point-based method converge to the exact solution $\bar{z}$ as the degree of the approximate solution tends to infinity.

Proof. Given an arbitrary positive number $\epsilon > 0$, by the Weierstrass theorem (see [21]) one can easily find polynomials $Q_{1,N_1}(t)$ of degree N_1 such that

$$\|a - Q_{1,N_1}(0)\|_\infty \leq \frac{\epsilon}{16},$$

where $\|\cdot\|_\infty$ stands for the L_∞ -norm over $[0, 1]$.

In general, $Q_{1,N_1}(t)$ does not satisfy the boundary conditions. After a small perturbation with linear and constant polynomials β , for $Q_{1,N_1}(t)$, we can obtain a polynomial $P_{1,N_1}(t) = Q_{1,N_1}(t) + \beta$ such that $P_{1,N_1}(t)$ satisfies the boundary condition $P_{1,N_1}(0) = a$. Thus $Q_{1,N_1}(0) + \beta = a$. Then, we have

$$\begin{aligned} \|a - Q_{1,N_1}(0)\|_\infty &= \|\beta\|_\infty \leq \frac{\epsilon}{16}, \\ \|{}^c D_p^\beta P_{1,N_1}(t) - {}^c D_p^\beta \bar{z}(t)\|_\infty &= \left\| D_p^\beta \left((P_{1,N_1}(t) - \bar{z}(t)) - \sum_{j=0}^{n-1} \frac{D_p^j (P_{1,N_1}(0) - \bar{z}(0))}{\Gamma_p(j+1)} t^j \right) \right\|_\infty \\ &\leq \|D_p^\beta (P_{1,N_1}(t) - \bar{z}(t))\|_\infty < \frac{\epsilon}{5}, \end{aligned}$$

Now, let define

$$LP_N(t) = L(P_{1,N_1}(t), {}^c D_p^\beta P_{1,N_1}(t)) = {}^c D_p^\beta P_{1,N_1}(t) - A(t)P_{1,N_1}(t) = F(t),$$

for every $t \in [0, 1]$. Thus for $N \geq N_1$, we have an upper bound for the following residual:

$$\begin{aligned} \|LP_N(t) - F(t)\|_\infty &= \|L(P_{1,N_1}(t), {}^c D_p^\beta P_{1,N_1}(t))\|_\infty \leq \|{}^c D_p^\beta P_{1,N_1}(t) - {}^c D_p^\beta \bar{z}(t)\|_\infty + \|A(t)\|_\infty \|P_{1,N_1}(t) - \bar{z}(t)\|_\infty \\ &\leq C_1 \left(\frac{\epsilon}{5} + \frac{\epsilon}{5} \right) < C_1 \epsilon, \end{aligned}$$

where $C_1 = 1 + \|A(t)\|_\infty$ is a constant. Since the residual $R(P_N) := LP_N(t) - F(t)$ is a polynomial, we can represent it in Bézier form. Therefore

$$R(P_N) := \sum_{i=0}^{m_1} d_{i,m_1} B_{i,m_1}(t),$$



then from Lemma 1 in [27], there exists an integer $M(\geq N)$ such that when $m_1 > M$, we have

$$\left| \frac{1}{m_1 + 1} \sum_{i=0}^{m_1} d_{i,m_1}^2 - \int_0^1 (R(P_N))^2 dt \right| < \epsilon,$$

thus

$$\frac{1}{m_1 + 1} \sum_{i=0}^{m_1} d_{i,m_1}^2 < \epsilon + \int_0^1 (R(P_N))^2 dt < \epsilon + C_1^2 \epsilon^2.$$

Suppose $z(t)$ is approximated solution of (4.3) obtained by the control-point-based method of degree m_2 ($m_2 \geq m_1 \geq M$). Let

$$R(z(t), {}^c D_p^\beta P_{1,N_1}(t)) = L(z(t), {}^c D_p^\beta P_{1,N_1}(t)) - F(t) = \sum_{i=0}^{m_2} c_{i,m_2} B_{i,m_2}(t), m_2 \geq m_1 \geq M, t \in [0, 1].$$

Define the following norm for difference approximated solution $z(t)$ and exact solution $\bar{z}(t)$

$$\|z(t) - \bar{z}(t)\| := \int_0^1 |{}^c D_p^\beta z(t) - {}^c D_p^\beta \bar{z}(t)|^2 dt. \quad (4.4)$$

By (4.4), Lemma 4.3, the boundary conditions $\bar{z}(0) = a = P_{1,N_1}(0) = z(0)$, we have

$$\begin{aligned} \|z(t) - \bar{z}(t)\| &\leq C|z(0) - \bar{z}(0)| + \|R((z(t), {}^c D_p^\beta z(t)) - (\bar{z}(t), {}^c D_p^\beta \bar{z}(t)))\|_2^2 \\ &= C \int_0^1 \sum_{i=0}^{m_2} (c_{i,m_2} B_{i,m_2}(t))^2 dt \leq \frac{C}{m_2 + 1} \sum_{i=0}^{m_2} c_{i,m_2}^2. \end{aligned} \quad (4.5)$$

The last inequality in (4.5) is obtained by Lemma 4.3, where C is a constant positive number. Hence

$$\begin{aligned} \|z(t) - \bar{z}(t)\| &\leq \frac{C}{m_2 + 1} \sum_{i=0}^{m_2} c_{i,m_2}^2 \\ &\leq \frac{C}{m_2 + 1} \sum_{i=0}^{m_2} d_{i,m_2}^2 \leq \frac{C}{m_1 + 1} \sum_{i=0}^{m_1} d_{i,m_1}^2 \\ &\leq C(\epsilon + C_1^2 \epsilon^2) = \epsilon_1, \quad m_1 \geq M. \end{aligned}$$

This completes the proof. $\square$

5. NUMERICAL EXAMPLES

Now, a numerical example of IVPCpF is presented to illustrate the BCM (Bézier Curve Method). By utilizing Maple 16, all results are obtained.

Example 5.1. We will examine our method by applying it to the following IVPCpF discussed in ([25]) as given below:

$$\begin{aligned} {}^c D_p^{\frac{1}{3}} z(t) &= t^{-\frac{3}{2}} z^2(t), \quad 0 < t \leq 1, \quad z(0) = 10^{-4}, \\ z_{\text{exact}}(t) &= \Gamma_p(13/6) t^{\frac{7}{6}} / \Gamma_p(11/6) + 10^{-4}. \end{aligned}$$

By BCM and the collocation points p^{N-i} ($N = 10, i = 0, 1, \dots, N, \beta = \frac{1}{3}$), we obtain Tables 1 and 2. The solution graphs z can be revealed in Figure 1 (with $n = 3$).

Example 5.2. The following IVPCpF is considered (see [26])

$$\begin{aligned} {}^c D_p^\beta z(t) &= t, \quad 0 < t \leq 1, \quad z(0) = z_0 = 0 \\ z_{\text{exact}}(t) &= \frac{\Gamma_p(2)}{\Gamma_p(\frac{5}{2})} t^{\frac{3}{2}}. \end{aligned}$$



TABLE 1. Absolute error of $z(t)$ for this method and error in [25] for Example 5.1 ($N = 10, \beta = \frac{1}{3}, p = \frac{1}{2}$).

t	Absolute error in BCM	Absolute error in [25]
$\frac{1}{10^{24}}$	$0.307597912584070 \times 10^{-3}$	—
$\frac{1}{5^{12}}$	$4.58331289587832 \times 10^{-14}$	7.48751×10^{-4}
$\frac{1}{25^6}$	0.000190894208127339	1.69380×10^{-3}
$\frac{1}{128}$	$5.70704941638134 \times 10^{-13}$	3.80772×10^{-3}
$\frac{1}{64}$	$4.88584867008868 \times 10^{-13}$	8.55030×10^{-3}
$\frac{1}{32}$	0.000103365853560924	1.19196×10^{-2}
$\frac{1}{16}$	$1.32436422939364 \times 10^{-11}$	4.30935×10^{-2}
$\frac{1}{8}$	0.00398404087914093	9.67418×10^{-2}
$\frac{1}{4}$	$3.90912302528079 \times 10^{-12}$	2.17178×10^{-1}
$\frac{1}{2}$	0.0388958273590442	4.87548×10^{-1}
1	0.0159066965555552	1.09451

TABLE 2. Absolute error of $z(t)$ for this method and error in [25] and [12] for Example 5.1 ($N = 10, \beta = \frac{1}{3}, p = \frac{1}{8}$).

t	Absolute error in BCM	Absolute error in [25]	Absolute error in [12]
$\frac{1}{8^{10}}$	$2.91031474126313 \times 10^{-11}$	—	—
$\frac{1}{8^9}$	$0.77659237026844 \times 10^{-14}$	7.10653×10^{-4}	1.35645×10^{-4}
$\frac{1}{8^8}$	$4.40869352346390 \times 10^{-10}$	1.59919×10^{-3}	1.35642×10^{-4}
$\frac{1}{8^7}$	$4.77766630895614 \times 10^{-14}$	3.59173×10^{-3}	1.35607×10^{-4}
$\frac{1}{8^6}$	$3.87464026063499 \times 10^{-14}$	8.06390×10^{-3}	1.35208×10^{-4}
$\frac{1}{8^5}$	0.00000193727690609905	1.81032×10^{-2}	1.30952×10^{-4}
$\frac{1}{8^4}$	$1.87868519569215 \times 10^{-14}$	4.06404×10^{-2}	1.05923×10^{-4}
$\frac{1}{8^3}$	0.000212000148251494	9.12346×10^{-2}	3.61824×10^{-3}
$\frac{1}{8^2}$	$3.88074988810772 \times 10^{-13}$	2.04815×10^{-1}	2.24448×10^{-3}
$\frac{1}{8}$	0.0144815408959622	4.59794×10^{-1}	7.76074×10^{-3}
1	$4.27017088355797 \times 10^{-10}$	1.03220	6.37084×10^{-3}

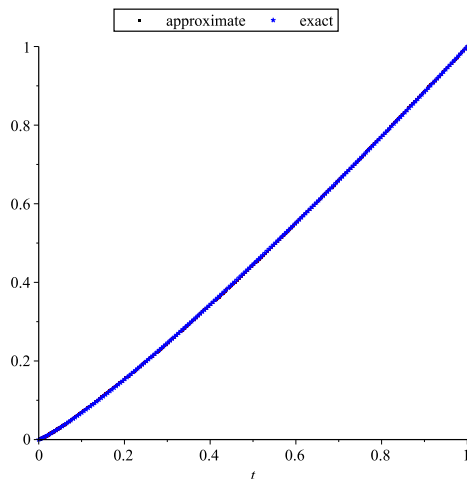
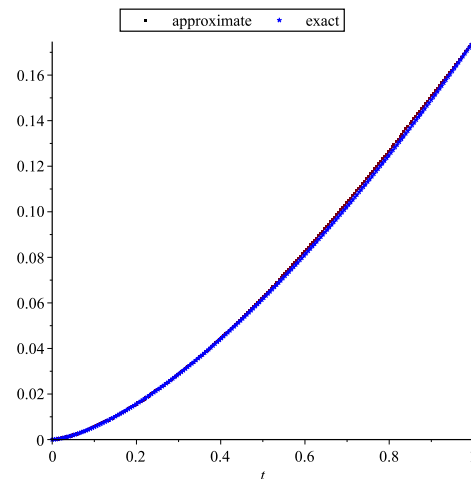
FIGURE 1. The graphs of approximated and exact solution $z(t)$ for Example 5.1 with $p = \frac{1}{2}$.FIGURE 2. The graphs of approximated and exact solution $z(t)$ for Example 5.2 with $p = \frac{1}{2}, \beta = \frac{1}{3}$.

TABLE 3. Absolute error for $z(t)$ for Example 5.2 with $p = \frac{1}{2}, \beta = \frac{1}{3}$.

t	Absolute error for this method
$\frac{1}{10^{24}}$	0.0000305175781200000
$\frac{1}{5^{12}}$	$4.44582521838544 \times 10^{-15}$
$\frac{1}{2^{56}}$	0.0000166726728261375
$\frac{1}{128}$	$1.10127076728694 \times 10^{-13}$
$\frac{1}{64}$	$1.24925243760732 \times 10^{-13}$
$\frac{1}{32}$	0.0000533475738786126
$\frac{1}{16}$	$5.24244536670437 \times 10^{-12}$
$\frac{1}{8}$	0.000597492837855075
$\frac{1}{4}$	$3.08431058471115 \times 10^{-12}$
$\frac{1}{2}$	0.00477994278497773
1	$3.35516503469080 \times 10^{-10}$

TABLE 4. Absolute error of $z(t)$ for this method and error in for Example 5.2 ($N = 20, p = \frac{3}{5}, \beta = \frac{1}{2}$).

t	Absolute error in BCM	Absolute error in [26]
$(3/5)^{19}$	$1.14677656602779 \times 10^{-16}$	4.44849×10^{-8}
$(3/5)^{18}$	$2.04019525271454 \times 10^{-8}$	—
$(3/5)^{17}$	$.36421444095043 \times 10^{-16}$	2.29471×10^{-8}
$(3/5)^{16}$	$9.75353885961235 \times 10^{-16}$	—
$(3/5)^{15}$	$6.80935073576306 \times 10^{-9}$	1.20204×10^{-7}
$(3/5)^{14}$	$4.83832736889063 \times 10^{-15}$	—
$(3/5)^{13}$	$4.54327696255453 \times 10^{-8}$	5.72027×10^{-8}
$(3/5)^{12}$	$2.20320829349898 \times 10^{-14}$	—
$(3/5)^{11}$	$2.10336874006543 \times 10^{-7}$	3.23198×10^{-8}
$(3/5)^{10}$	$1.34127287726958 \times 10^{-13}$	—
$(3/5)^9$	0.00556820984512183	1.90138×10^{-8}
$(3/5)^8$	$1.95646801439808 \times 10^{-12}$	—
$(3/5)^7$	$1.47896693264600 \times 10^{-12}$	1.13302×10^{-8}
$(3/5)^6$	$5.95253490595637 \times 10^{-12}$	—
$(3/5)^5$	.205852355915861	6.78151×10^{-9}
$(3/5)^4$	$8.38030166094850 \times 10^{-12}$	—
$(3/5)^3$	$2.01078628574158 \times 10^{-11}$	4.06534×10^{-9}
$(3/5)^2$	0.00283916294314055	—
$(3/5)^1$	$5.72063351550467 \times 10^{-11}$	1.22486×10^{-7}

By BCM and the collocation points p^{N-i} , we achieve Tables 3 and 4 and Figure 2 (with $n = 3$).

$$z(t) = \begin{cases} 0.01636697759t - 0.1558044172 \times 10^{-4} - 0.5024058425t^2 + 81.81560373t^3, & 0 \leq t \leq \frac{1}{2^7}, \\ -0.2262052280 \times 10^{-4} + 0.01296279721t + .7150983986t^2 - 3.486727697t^3, & \frac{1}{2^7} \leq t \leq \frac{1}{2^4}, \\ -0.9705441908 \times 10^{-3} + 0.04755666544t + 0.1902266620t^2 - 0.06211482836t^3, & \frac{1}{2^4} \leq t \leq 1. \end{cases}$$

Example 5.3. The following IVPcP is examined (see [25])

$${}^c D_p^{\frac{1}{2}} z(t) = t + t^2, \quad 0 < t \leq 1, \quad z(0) = z_0 = 1,$$

$$z_{\text{exact}}(t) = 1 + \frac{\Gamma_p(2)}{\Gamma_p(\frac{5}{2})} t^{\frac{3}{2}} + \frac{\Gamma_p(3)}{\Gamma_p(\frac{7}{2})} t^{\frac{5}{2}}.$$



TABLE 5. Absolute error for $z(t)$ for Example 5.3 with $p = \frac{1}{2}$.

t	Absolute error in BCM
$\frac{1}{10^{24}}$	$0.305472210352359 \times 10^{-4}$
$\frac{1}{5^{12}}$	$6.07360770651151 \times 10^{-10}$
$\frac{1}{2^{56}}$	$0.167348306401367 \times 10^{-4}$
$\frac{1}{1^{28}}$	$3.96908105022170 \times 10^{-10}$
$\frac{1}{6^4}$	$4.81004684528357 \times 10^{-10}$
$\frac{1}{3^2}$	$0.514451038466408 \times 10^{-4}$
$\frac{1}{1^6}$	$1.58913326941956 \times 10^{-10}$
$\frac{1}{8}$	$0.656960275817142 \times 10^{-3}$
$\frac{1}{4}$	$2.44828601836389 \times 10^{-11}$
$\frac{1}{2}$	$8.98517371616947 \times 10^{-11}$
1	$1.00654995449645 \times 10^{-9}$

By BCM and the collocation points p^{N-i} , we achieve Table 5 (with $n = 3$).

6. CONCLUSIONS

The approximate solution of IVPcP via BCM is introduced in this paper. The lemma is proved for the truncated error. This approach is computationally appealing, and decreases the computer's memory, at the same time improves the accuracy. Finally, several examples are provided to verify our theoretical analysis by utilizing the technique finding the approximate solutions of the IVPcP and compared with the previous existing methods in the literature. Comparing with others, the outcomes state that the technique is more accurate than others.

STATEMENTS AND DECLARATIONS

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Ethical approval. Not applicable.

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