

Triquintic interpolation in three dimensions

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Abstract

This paper develops a local triquintic interpolation method for a function defined over a unit cube mesh element. The resulting polynomial interpolant is isotropic and has global \mathcal{C}^2 continuity. The triquintic polynomial coefficients are related to the function and its derivatives at the eight corners of a mesh element by an invertible matrix of rank 216. The proposed method is an extension of a previously developed tricubic interpolation scheme with global \mathcal{C}^1 continuity.

Keywords: three-dimensional interpolation, triquintic interpolation, globally smooth interpolation
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1. Introduction

Tricubic interpolation have been used very successfully in a range of fields, including ocean dynamics [1], plasma dynamics [2], image processing [3], particle physics [4], computational chemistry [5, 6, 7] and structural biology [8]. Lekien and Marsden (LM) [9] developed an isotropic tricubic interpolation scheme that did not separate the interpolant into a tensor product of three one-dimensional polynomials. Compared to the tensor product approach, the method due to LM has a reduced computational cost and provides easy access to more accurate derivatives. Lekien and Marsden also showed that their method has global \mathcal{C}^1 continuity but cannot achieve global \mathcal{C}^2 continuity.

There is a need for higher order interpolants with a concomitant increase in smoothness. For example, it has been observed that, in particle simulations, the smoothness of the tricubic interpolation has an effect on the accuracy of the dynamics [2, 6, 7]. Additionally, in applications where second order derivatives of the interpolated kernel are required, such as in molecular dynamics simulations with dipoles, tricubic interpolation will not be very effective because of the lack of global \mathcal{C}^2 continuity.

This paper is a response to the need for higher order nontensorial interpolants. A search of the literature shows that triquintic interpolation has been implemented in cosmological simulations [10] and in fracture mechanics [11]. However, neither of these two works provide details about their implementation nor a study of the continuity and convergence properties of their interpolator. We extend the work of LM to systematically develop a triquintic interpolation method that is also isotropic. We prove that the method is globally \mathcal{C}^2 continuous but lacks global \mathcal{C}^3 continuity. We also prove that the error for the tricubic interpolant decays as a quadratic while the error for the triquintic interpolant decays as a cubic. Finally, we provide numerical evidence of the decay rate

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of the errors and the accuracy of the tricubic and triquintic interpolations using two functions, $f(x, y, z) = \frac{1}{\sqrt{x^2 + y^2 + z^2 + \delta}}$ and $g(x, y, z) = (x^2 + y^2 + z^2) e^{-(x^2 + y^2 + z^2)}$.

The paper is organized as follows. In Section 2 we describe the tricubic interpolation method developed by Lekien and Marsden [9]. We develop the triquintic interpolation method in Section 3. In Section 4, we prove that the triquintic method is globally \mathcal{C}^2 continues and that it lacks global \mathcal{C}^3 continuity. We derive the convergence rate of the interpolants supported by numerical evidence in Section 5 and summarize our conclusions in Section 6.

2. Tricubic interpolation

Let the function f be defined over a three dimensional rectilinear mesh. Then f is interpolated

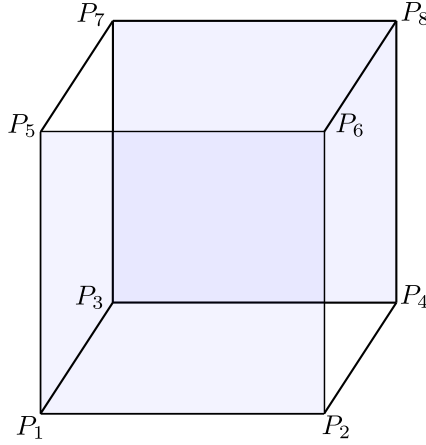


Figure 1: The unit cube mesh element.

on and inside the unit cube mesh element (represented in Figure 1) by the polynomial

$$\mathcal{P}(x, y, z) = \sum_{i,j,k=0}^3 a_{ijk} x^i y^j z^k = \boldsymbol{\alpha}^T \boldsymbol{\mu}, \quad (1)$$

where the 64 unknown coefficients a_{ijk} are ordered into a vector $\boldsymbol{\alpha}$ by defining

$$\alpha_{1+i+4j+16k} = a_{ijk}, \quad i, j, k = 0, 1, 2, 3, \quad (2)$$

and the monomials $x^i y^j z^k$ are ordered into the vector $\boldsymbol{\mu}$ through a similar definition

$$\mu_{1+i+4j+16k} = x^i y^j z^k, \quad i, j, k = 0, 1, 2, 3. \quad (3)$$

To determine the 64 coefficients a_{ijk} , LM enforced the following 8 linearly independent constraints

$$\left\{ \begin{aligned} \mathcal{P} &= f, \quad \frac{\partial \mathcal{P}}{\partial x} = \frac{\partial f}{\partial x}, \quad \frac{\partial \mathcal{P}}{\partial y} = \frac{\partial f}{\partial y}, \quad \frac{\partial \mathcal{P}}{\partial z} = \frac{\partial f}{\partial z}, \\ \frac{\partial^2 \mathcal{P}}{\partial x \partial y} &= \frac{\partial^2 f}{\partial x \partial y}, \quad \frac{\partial^2 \mathcal{P}}{\partial x \partial z} = \frac{\partial^2 f}{\partial x \partial z}, \quad \frac{\partial^2 \mathcal{P}}{\partial y \partial z} = \frac{\partial^2 f}{\partial y \partial z}, \quad \frac{\partial^3 \mathcal{P}}{\partial x \partial y \partial z} = \frac{\partial^3 f}{\partial x \partial y \partial z} \end{aligned} \right\}, \quad (4)$$

at the eight vertices of the unit cube to generate a full rank sparse linear system

$$B\boldsymbol{\alpha} = \mathbf{b}. \quad (5)$$

Here B is the 64×64 invertible coefficient matrix generated by applying the constraints to the polynomial and \mathbf{b} is obtained from applying the constraints to the function. This choice of constraints is the only set that yields an isotropic interpolant with global \mathcal{C}^1 continuity. The coefficient vector is computed explicitly as $\boldsymbol{\alpha} = B^{-1}\mathbf{b}$. The matrix B^{-1} is independent of the function being interpolated and can be stored to be reused for different evaluation points within the mesh and for different functions. This feature is the main reason why the LM tricubic has less computational cost compared to the tensor product version.

3. Triquintic interpolation

The triquintic interpolant is defined over the same unit cube, depicted in Figure 1, as the tricubic. A function f is represented locally on and inside the unit cube by the polynomial

$$\mathcal{P}(x, y, z) = \sum_{i,j,k=0}^5 a_{ijk} x^i y^j z^k = \boldsymbol{\alpha}^T \boldsymbol{\mu}. \quad (6)$$

The elements of the vector $\boldsymbol{\alpha}$ are given by

$$\alpha_{1+i+6j+36k} = a_{ijk}, \quad i, j, k = 0, 1, 2, 3, 4, 5, \quad (7)$$

and the elements of the vector $\boldsymbol{\mu}$ are similarly ordered as

$$\mu_{1+i+6j+36k} = x^i y^j z^k, \quad i, j, k = 0, 1, 2, 3, 4, 5. \quad (8)$$

We need 216 linearly independent constraints to determine the 216 coefficients a_{ijk} . Following LM [9], our constraints will be defined at the eight vertices of the unit cube. Thus we require 27 constraints repeated at each vertex. We would like the interpolant to be isotropic and to achieve global \mathcal{C}^2 continuity.

3.1. Constraints for triquintic interpolation

Because we want the interpolant to be at least globally \mathcal{C}^2 continuous, the function and all its first and second derivatives must agree with the polynomial at the vertices of the cube which leads to the 10 constraints

$$\left\{ \begin{aligned} \mathcal{P} &= f, \quad \frac{\partial \mathcal{P}}{\partial x} = \frac{\partial f}{\partial x}, \quad \frac{\partial \mathcal{P}}{\partial y} = \frac{\partial f}{\partial y}, \quad \frac{\partial \mathcal{P}}{\partial z} = \frac{\partial f}{\partial z}, \quad \frac{\partial^2 \mathcal{P}}{\partial x^2} = \frac{\partial^2 f}{\partial x^2}, \\ \frac{\partial^2 \mathcal{P}}{\partial x \partial y} &= \frac{\partial^2 f}{\partial x \partial y}, \quad \frac{\partial^2 \mathcal{P}}{\partial x \partial z} = \frac{\partial^2 f}{\partial x \partial z}, \quad \frac{\partial^2 \mathcal{P}}{\partial y^2} = \frac{\partial^2 f}{\partial y^2}, \quad \frac{\partial^2 \mathcal{P}}{\partial y \partial z} = \frac{\partial^2 f}{\partial y \partial z}, \quad \frac{\partial^2 \mathcal{P}}{\partial z^2} = \frac{\partial^2 f}{\partial z^2} \end{aligned} \right\}. \quad (9)$$

Next, we match the third derivatives. First, we note that along any axis, the triquintic interpolant is just a fifth degree spline whose 6 coefficients are uniquely determined by the value of the function and its first and second derivatives at the endpoints of the interval. As such, constraints involving derivatives of the form

$$\frac{\partial^\nu \mathcal{P}}{\partial s^\nu}, \quad \nu \geq 3, \quad s \in \{x, y, z\}, \quad (10)$$

are dependent on the function and its first and second derivatives and thus are extraneous. As an example, consider the interpolant along the x -axis ($y = z = 0$),

$$\mathcal{P}(x, 0, 0) = \sum_{i=0}^5 a_{i00} x^i = a_{000} + a_{100}x + a_{200}x^2 + a_{300}x^3 + a_{400}x^4 + a_{500}x^5, \quad (11)$$

$$\frac{\partial \mathcal{P}}{\partial x} = \sum_{i=1}^5 i a_{i00} x^{i-1} = a_{100} + 2a_{200}x + 3a_{300}x^2 + 4a_{400}x^3 + 5a_{500}x^4, \quad (12)$$

$$\frac{\partial^2 \mathcal{P}}{\partial x^2} = \sum_{i=2}^5 i(i-1) a_{i00} x^{i-2} = 2a_{200} + 6a_{300}x + 12a_{400}x^2 + 20a_{500}x^3, \quad (13)$$

$$\frac{\partial^3 \mathcal{P}}{\partial x^3} = \sum_{i=3}^5 i(i-1)(i-2) a_{i00} x^{i-3} = 6a_{300} + 24a_{400}x + 60a_{500}x^2. \quad (14)$$

Evaluating Equations (11) to (14) at the left and right endpoints of the spline interval, $P_1 = (0, 0, 0)$ and $P_2 = (1, 0, 0)$ respectively, we get

$$\mathcal{P}|_{(0,0,0)} = a_{000}, \quad \frac{\partial \mathcal{P}}{\partial x}|_{(0,0,0)} = a_{100}, \quad \frac{\partial^2 \mathcal{P}}{\partial x^2}|_{(0,0,0)} = 2a_{200}, \quad \frac{\partial^3 \mathcal{P}}{\partial x^3}|_{(0,0,0)} = 6a_{300}, \quad (15)$$

$$\mathcal{P}|_{(1,0,0)} = a_{000} + a_{100} + a_{200} + a_{300} + a_{400} + a_{500}, \quad (16)$$

$$\frac{\partial \mathcal{P}}{\partial x}|_{(1,0,0)} = a_{100} + 2a_{200} + 3a_{300} + 4a_{400} + 5a_{500}, \quad (17)$$

$$\frac{\partial^2 \mathcal{P}}{\partial x^2}|_{(1,0,0)} = 2a_{200} + 6a_{300} + 12a_{400} + 20a_{500}, \quad (18)$$

$$\frac{\partial^3 \mathcal{P}}{\partial x^3}|_{(1,0,0)} = 6a_{300} + 24a_{400} + 60a_{500}. \quad (19)$$

We observe that

$$\begin{aligned} \frac{\partial^3 \mathcal{P}}{\partial x^3}|_{(0,0,0)} = & -60\mathcal{P}|_{(0,0,0)} + 60\mathcal{P}|_{(1,0,0)} - 36\frac{\partial \mathcal{P}}{\partial x}|_{(0,0,0)} - 24\frac{\partial \mathcal{P}}{\partial x}|_{(1,0,0)} \\ & - 9\frac{\partial^2 \mathcal{P}}{\partial x^2}|_{(0,0,0)} + 3\frac{\partial^2 \mathcal{P}}{\partial x^2}|_{(1,0,0)}, \end{aligned} \quad (20)$$

and

$$\begin{aligned} \frac{\partial^3 \mathcal{P}}{\partial x^3}|_{(1,0,0)} = & -60\mathcal{P}|_{(0,0,0)} + 60\mathcal{P}|_{(1,0,0)} - 24\frac{\partial \mathcal{P}}{\partial x}|_{(0,0,0)} - 36\frac{\partial \mathcal{P}}{\partial x}|_{(1,0,0)} \\ & - 3\frac{\partial^2 \mathcal{P}}{\partial x^2}|_{(0,0,0)} + 9\frac{\partial^2 \mathcal{P}}{\partial x^2}|_{(1,0,0)}, \end{aligned} \quad (21)$$

thus we omit the constraint $\frac{\partial^3 \mathcal{P}}{\partial x^3} = \frac{\partial^3 f}{\partial x^3}$. Similarly, by symmetry, we omit the constraints $\frac{\partial^3 \mathcal{P}}{\partial y^3} = \frac{\partial^3 f}{\partial y^3}$ and $\frac{\partial^3 \mathcal{P}}{\partial z^3} = \frac{\partial^3 f}{\partial z^3}$. The remaining set of third derivatives provide the 7 constraints

$$\begin{aligned} & \left\{ \frac{\partial^3 \mathcal{P}}{\partial x^2 \partial y} = \frac{\partial^3 f}{\partial x^2 \partial y}, \quad \frac{\partial^3 \mathcal{P}}{\partial x^2 \partial z} = \frac{\partial^3 f}{\partial x^2 \partial z}, \quad \frac{\partial^3 \mathcal{P}}{\partial x \partial y^2} = \frac{\partial^3 f}{\partial x \partial y^2}, \right. \\ & \left. \frac{\partial^3 \mathcal{P}}{\partial x \partial y \partial z} = \frac{\partial^3 f}{\partial x \partial y \partial z}, \quad \frac{\partial^3 \mathcal{P}}{\partial y^2 \partial z} = \frac{\partial^3 f}{\partial y^2 \partial z}, \quad \frac{\partial^3 \mathcal{P}}{\partial x \partial z^2} = \frac{\partial^3 f}{\partial x \partial z^2}, \quad \frac{\partial^3 \mathcal{P}}{\partial y \partial z^2} = \frac{\partial^3 f}{\partial y \partial z^2} \right\}, \end{aligned} \quad (22)$$

which are invariant under a rotation of the axis and thus maintain the isotropic property. The final 10 constraints are given by the fourth, fifth and sixth order derivatives which do not involve derivatives of the form given in Equation (10). These 10 constraints are

$$\left\{ \frac{\partial^4 \mathcal{P}}{\partial x^2 \partial y^2} = \frac{\partial^4 f}{\partial x^2 \partial y^2}, \frac{\partial^4 \mathcal{P}}{\partial x^2 \partial z^2} = \frac{\partial^4 f}{\partial x^2 \partial z^2}, \frac{\partial^4 \mathcal{P}}{\partial y^2 \partial z^2} = \frac{\partial^4 f}{\partial y^2 \partial z^2}, \right. \quad (23)$$

$$\left. \frac{\partial^4 \mathcal{P}}{\partial x^2 \partial y \partial z} = \frac{\partial^4 f}{\partial x^2 \partial y \partial z}, \frac{\partial^4 \mathcal{P}}{\partial x \partial y^2 \partial z} = \frac{\partial^4 f}{\partial x \partial y^2 \partial z}, \frac{\partial^4 \mathcal{P}}{\partial x \partial y \partial z^2} = \frac{\partial^4 f}{\partial x \partial y \partial z^2} \right\},$$

$$\left\{ \frac{\partial^5 \mathcal{P}}{\partial x^2 \partial y^2 \partial z} = \frac{\partial^5 f}{\partial x^2 \partial y^2 \partial z}, \frac{\partial^5 \mathcal{P}}{\partial x^2 \partial y \partial z^2} = \frac{\partial^5 f}{\partial x^2 \partial y \partial z^2}, \frac{\partial^5 \mathcal{P}}{\partial x \partial y^2 \partial z^2} = \frac{\partial^5 f}{\partial x \partial y^2 \partial z^2} \right\}, \quad (24)$$

and

$$\left\{ \frac{\partial^6 \mathcal{P}}{\partial x^2 \partial y^2 \partial z^2} = \frac{\partial^6 f}{\partial x^2 \partial y^2 \partial z^2} \right\}. \quad (25)$$

These last 10 constraints are also invariant under axis rotation, thus the interpolant is isotropic.

3.2. The triquintic linear system

To determine the 216 coefficients, the 27 constraints are enforced at the eight vertices of the cube, P_1, \dots, P_8 to generate the full rank system defined in Equation (5). We order the elements b_i in vector \mathbf{b} , and hence the rows of matrix B , by defining

$$b_i = \begin{cases} f(P_i), & 1 \leq i \leq 8, & \frac{\partial^2 f(P_{i-72})}{\partial z^2}, & 73 \leq i \leq 80, & \frac{\partial^4 f(P_{i-144})}{\partial x^2 \partial z^2}, & 145 \leq i \leq 152 \\ \frac{\partial f(P_{i-8})}{\partial x}, & 9 \leq i \leq 16, & \frac{\partial^3 f(P_{i-80})}{\partial x^2 \partial y}, & 81 \leq i \leq 88, & \frac{\partial^4 f(P_{i-152})}{\partial y^2 \partial z^2}, & 153 \leq i \leq 160 \\ \frac{\partial f(P_{i-16})}{\partial y}, & 17 \leq i \leq 24, & \frac{\partial^3 f(P_{i-88})}{\partial x^2 \partial z}, & 89 \leq i \leq 96, & \frac{\partial^4 f(P_{i-160})}{\partial x^2 \partial y \partial z}, & 161 \leq i \leq 168 \\ \frac{\partial f(P_{i-24})}{\partial z}, & 25 \leq i \leq 32, & \frac{\partial^3 f(P_{i-96})}{\partial x \partial y^2}, & 97 \leq i \leq 104, & \frac{\partial^4 f(P_{i-168})}{\partial x \partial y^2 \partial z}, & 169 \leq i \leq 176 \\ \frac{\partial^2 f(P_{i-32})}{\partial x^2}, & 33 \leq i \leq 40, & \frac{\partial^3 f(P_{i-104})}{\partial x \partial y \partial z}, & 105 \leq i \leq 112, & \frac{\partial^4 f(P_{i-176})}{\partial x \partial y \partial z^2}, & 177 \leq i \leq 184 \\ \frac{\partial^2 f(P_{i-40})}{\partial x \partial y}, & 41 \leq i \leq 48, & \frac{\partial^3 f(P_{i-112})}{\partial y^2 \partial z}, & 113 \leq i \leq 120, & \frac{\partial^5 f(P_{i-184})}{\partial x^2 \partial y^2 \partial z}, & 185 \leq i \leq 192 \\ \frac{\partial^2 f(P_{i-48})}{\partial x \partial z}, & 49 \leq i \leq 56, & \frac{\partial^3 f(P_{i-120})}{\partial x \partial z^2}, & 121 \leq i \leq 128, & \frac{\partial^5 f(P_{i-192})}{\partial x^2 \partial y \partial z}, & 193 \leq i \leq 200 \\ \frac{\partial^2 f(P_{i-56})}{\partial y^2}, & 57 \leq i \leq 64, & \frac{\partial^3 f(P_{i-128})}{\partial y \partial z^2}, & 129 \leq i \leq 136, & \frac{\partial^5 f(P_{i-200})}{\partial x \partial y^2 \partial z^2}, & 201 \leq i \leq 208 \\ \frac{\partial^2 f(P_{i-64})}{\partial y \partial z}, & 65 \leq i \leq 72, & \frac{\partial^4 f(P_{i-136})}{\partial x^2 \partial y^2}, & 137 \leq i \leq 144, & \frac{\partial^6 f(P_{i-208})}{\partial x^2 \partial y^2 \partial z^2}, & 209 \leq i \leq 216 \end{cases} \quad (26)$$

We solve for the coefficients as $\alpha = B^{-1}\mathbf{b}$ and the polynomial defined in Equation (6) becomes

$$\mathcal{P}(x, y, z) = \mathbf{b}^T (B^{-1})^T \boldsymbol{\mu}. \quad (27)$$

The matrix B^{-1} is sparse with 9261 non-zero elements. Because the matrix depends only on the unit cube mesh and not on the function being interpolated, it is stored and reused. The scaled matrix $8B$ is available online [12].

4. Smoothness property of the isotropic triquintic interpolant

Now, we study the smoothness property of the triquintic interpolant. First, we prove that the interpolant has global \mathcal{C}^2 continuity. Then we show that global \mathcal{C}^3 continuity does not hold for the triquintic interpolant. The triquintic polynomial interpolant $\mathcal{P}(x, y, z)$ is \mathcal{C}^∞ inside any mesh element and as such, its global smoothness is determined by the smoothness properties at the boundary of each mesh element. Following LM, we will focus our analysis on the common boundary(face)

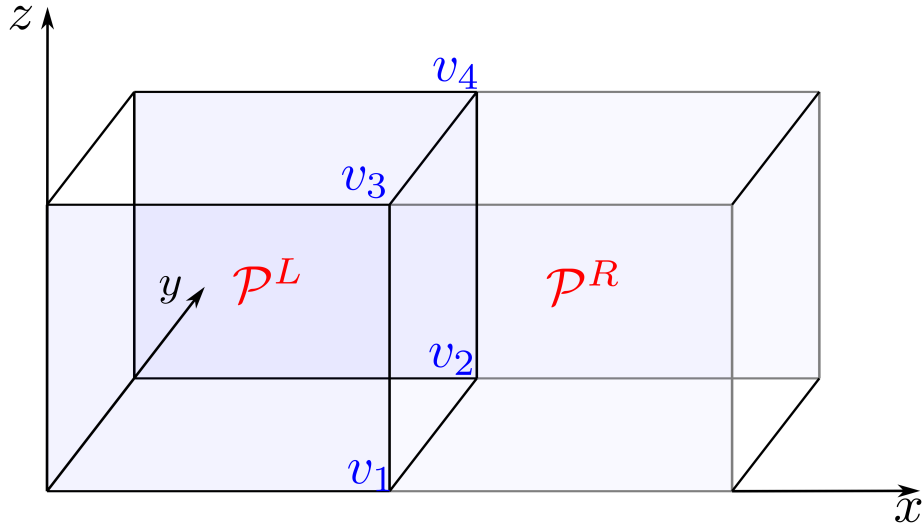


Figure 2: Adjacent mesh elements.

(v_1, v_3, v_4, v_2) between two adjacent mesh elements in Figure 2. By symmetry, the analysis will apply to the other faces.

4.1. Proof of global \mathcal{C}^2 continuity

Lemma 1. *The triquintic interpolant \mathcal{P} is everywhere continuous.*

Proof. Consider the adjacent mesh elements in Figure 2 and their boundary (v_1, v_3, v_4, v_2) . Our goal is to show that at the boundary (v_1, v_3, v_4, v_2) , the interpolant in the left mesh element, \mathcal{P}^L , is equal to the interpolant in the right mesh element, \mathcal{P}^R , which is sufficient to prove continuity across the boundary.

For \mathcal{P}^L , $x = 1$ at the boundary, thus

$$\mathcal{P}^L(1, y, z) = \sum_{j,k=0}^5 \left(\sum_{i=0}^5 a_{ijk} \right) y^j z^k = (\alpha^L)^T \boldsymbol{\mu}^L, \quad (28)$$

where the elements of vector α^L are ordered as

$$\alpha_{1+j+6k}^L = \sum_{i=0}^5 a_{ijk}, \quad j, k = 0, 1, 2, 3, 4, 5, \quad (29)$$

and the elements of vector μ^L are similarly ordered as

$$\mu_{1+j+6k}^L = y^j z^k, \quad j, k = 0, 1, 2, 3, 4, 5. \quad (30)$$

For \mathcal{P}^R , $x = 0$ at the boundary, hence

$$\mathcal{P}^L(0, y, z) = \sum_{j,k=0}^5 a_{0jk} y^j z^k = (\alpha^R)^T \mu^R, \quad (31)$$

with the elements of vectors α^R and μ^R ordered as

$$\alpha_{1+j+6k}^R = a_{0jk}, \quad j, k = 0, 1, 2, 3, 4, 5, \quad (32)$$

and

$$\mu_{1+j+6k}^R = y^j z^k, \quad j, k = 0, 1, 2, 3, 4, 5, \quad (33)$$

respectively. Now notice that $\mu^L = \mu^R$, thus to show that $\mathcal{P}_L = \mathcal{P}^R$ on the boundary, we only need to show that $\alpha^L = \alpha^R$. We solve for α^L from the linear system

$$B^L \alpha^L = \mathbf{b}^L, \quad (34)$$

and for α^R from the linear system

$$B^R \alpha^L = \mathbf{b}^R. \quad (35)$$

At the four vertices $\{v_1, v_2, v_3, v_4\}$, we enforce the subset of the original 27 set of constraints

$$\left\{ \mathcal{P} = f, \quad \frac{\partial \mathcal{P}}{\partial y} = \frac{\partial f}{\partial y}, \quad \frac{\partial \mathcal{P}}{\partial z} = \frac{\partial f}{\partial z}, \quad \frac{\partial^2 \mathcal{P}}{\partial y^2} = \frac{\partial^2 f}{\partial y^2}, \quad \frac{\partial^2 \mathcal{P}}{\partial y \partial z} = \frac{\partial^2 f}{\partial y \partial z}, \right. \\ \left. \frac{\partial^2 \mathcal{P}}{\partial z^2} = \frac{\partial^2 f}{\partial z^2}, \quad \frac{\partial^3 \mathcal{P}}{\partial y^2 \partial z} = \frac{\partial^3 f}{\partial y^2 \partial z}, \quad \frac{\partial^3 \mathcal{P}}{\partial y \partial z^2} = \frac{\partial^3 f}{\partial y \partial z^2}, \quad \frac{\partial^4 \mathcal{P}}{\partial y^2 \partial z^2} = \frac{\partial^4 f}{\partial y^2 \partial z^2} \right\}. \quad (36)$$

which do not involve derivatives in x . These 9 constraints remain linearly independent since the larger set is linearly independent [13]. Because $\mu^L = \mu^R$, and the constraints are the same for both \mathcal{P}^L and \mathcal{P}^R , the coefficient matrices B^L and B^R in Equations (34) and (35) respectively, are the same (see reference [14] for the coefficient matrix). In addition, the right-hand sides \mathbf{b}^L and \mathbf{b}^R

depend only on the data f , as such

$$\mathbf{b}^L = \mathbf{b}^R = \begin{cases} f(v_i), & 1 \leq i \leq 4 \\ \frac{\partial^2 f}{\partial z^2}(v_{i-20}), & 21 \leq i \leq 24 \\ \frac{\partial f}{\partial y}(v_{i-4}), & 5 \leq i \leq 8 \\ \frac{\partial^3 f}{\partial y^2 \partial z}(v_{i-24}), & 25 \leq i \leq 28 \\ \frac{\partial f}{\partial z}(v_{i-8}), & 9 \leq i \leq 12 \\ \frac{\partial^3 f}{\partial y \partial z^2}(v_{i-28}), & 29 \leq i \leq 32 \\ \frac{\partial^2 f}{\partial y^2}(v_{i-12}), & 13 \leq i \leq 16 \\ \frac{\partial^4 f}{\partial y^2 \partial z^2}(v_{i-32}), & 33 \leq i \leq 36 \\ \frac{\partial^2 f}{\partial y \partial z}(v_{i-16}), & 17 \leq i \leq 20 \end{cases} \quad (37)$$

It follows then that

$$\boldsymbol{\alpha}^L = (B^L)^{-1} \mathbf{b}^L = (B^R)^{-1} \mathbf{b}^R = \boldsymbol{\alpha}^R, \quad (38)$$

hence $\mathcal{P}^L = \mathcal{P}^R$ and thus the interpolant is continuous across the boundary. Similar arguments for y and z , lead to the conclusion that the interpolant is continuous everywhere. \square

Lemma 2. *Derivatives of the form*

$$\frac{\partial^{\gamma+\nu} \mathcal{P}}{\partial y^\gamma \partial z^\nu}, \quad \gamma + \nu = 1, 2, 3, 4, 5, 6,$$

are continuous on the mesh element boundaries perpendicular to the x -axis.

Proof. From **Lemma 1**, $\mathcal{P}^L = \mathcal{P}^R$ on the boundary, (v_1, v_3, v_4, v_2) . Since the interpolants are polynomials in y and z , this means that their derivatives match to any order on the boundary. But (v_1, v_3, v_4, v_2) is an arbitrary boundary perpendicular to the x -axis, thus,

$$\frac{\partial^{\gamma+\nu} \mathcal{P}^L}{\partial y^\gamma \partial z^\nu} = \frac{\partial^{\gamma+\nu} \mathcal{P}^R}{\partial y^\gamma \partial z^\nu}, \quad \text{for } \gamma + \nu = 1, 2, 3, 4, 5, 6, \quad (39)$$

on mesh boundaries perpendicular to the x -axis. \square

Corollary 2.1. *Derivatives of the form*

$$\frac{\partial^{\gamma+\nu} \mathcal{P}}{\partial x^\gamma \partial y^\nu}, \quad \gamma + \nu = 1, 2, 3, 4, 5, 6,$$

are continuous on the mesh element boundaries perpendicular to the z -axis while derivatives of the form

$$\frac{\partial^{\gamma+\nu} \mathcal{P}}{\partial x^\gamma \partial z^\nu}, \quad \gamma + \nu = 1, 2, 3, 4, 5, 6,$$

are continuous on the mesh element boundaries perpendicular to the y -axis.

Proof. The corollary follows from **Lemma 1** and from **Lemma 2** by symmetry. \square

Lemma 3. *The polynomial $\frac{\partial \mathcal{P}}{\partial x}$ is continuous on the boundary (v_1, v_3, v_4, v_2) .*

Proof. Just as in the proof of **Lemma 1**, it suffices to show that $\frac{\partial \mathcal{P}^L}{\partial x}(1, y, z) = \frac{\partial \mathcal{P}^R}{\partial x}(0, y, z)$. We start by differentiating \mathcal{P} with respect to x to get

$$\frac{\partial \mathcal{P}}{\partial x}(x, y, z) = \sum_{j,k=0}^5 \sum_{i=1}^5 i a_{ijk} x^{i-1} y^j z^k. \quad (40)$$

On the boundary,

$$\frac{\partial \mathcal{P}^L}{\partial x}(1, y, z) = \sum_{j,k=0}^5 \left(\sum_{i=1}^5 i a_{ijk} \right) y^j z^k = (\boldsymbol{\alpha}^L)^T \boldsymbol{\mu}^L, \quad (41)$$

where

$$\alpha_{1+j+6k}^L = \sum_{i=1}^5 i a_{ijk}, \quad j, k = 0, 1, 2, 3, 4, 5, \quad (42)$$

and

$$\frac{\partial \mathcal{P}^R}{\partial x}(0, y, z) = \sum_{j,k=0}^5 a_{1jk} y^j z^k = (\boldsymbol{\alpha}^R)^T \boldsymbol{\mu}^R, \quad (43)$$

with

$$\alpha_{1+j+6k}^R = a_{1jk}, \quad j, k = 0, 1, 2, 3, 4, 5, \quad (44)$$

and

$$\mu_{1+j+6k}^L = \mu_{1+j+6k}^R = y^j z^k, \quad j, k = 0, 1, 2, 3, 4, 5. \quad (45)$$

Again, we have $\boldsymbol{\mu}^L = \boldsymbol{\mu}^R$, hence we only need to show that $\boldsymbol{\alpha}^L = \boldsymbol{\alpha}^R$. At the four vertices $\{v_1, v_2, v_3, v_4\}$, we enforce the following subset of the original set of constraints

$$\left. \begin{aligned} \left\{ \frac{\partial \mathcal{P}}{\partial x} = \frac{\partial f}{\partial x}, \quad \frac{\partial^2 \mathcal{P}}{\partial x \partial y} = \frac{\partial^2 f}{\partial x \partial y}, \quad \frac{\partial^2 \mathcal{P}}{\partial x \partial z} = \frac{\partial^2 f}{\partial x \partial z}, \quad \frac{\partial^3 \mathcal{P}}{\partial x \partial y^2} = \frac{\partial^3 f}{\partial x \partial y^2}, \quad \frac{\partial^3 \mathcal{P}}{\partial x \partial y \partial z} = \frac{\partial^3 f}{\partial x \partial y \partial z}, \right. \\ \left. \frac{\partial^3 \mathcal{P}}{\partial x \partial z^2} = \frac{\partial^3 f}{\partial x \partial z^2}, \quad \frac{\partial^4 \mathcal{P}}{\partial x \partial y^2 \partial z} = \frac{\partial^4 f}{\partial x \partial y^2 \partial z}, \quad \frac{\partial^4 \mathcal{P}}{\partial x \partial y \partial z^2} = \frac{\partial^4 f}{\partial x \partial y \partial z^2}, \quad \frac{\partial^5 \mathcal{P}}{\partial x \partial y^2 \partial z^2} = \frac{\partial^5 f}{\partial x \partial y^2 \partial z^2} \right\}. \end{aligned} \right\} \quad (46)$$

which involve just a single derivative in x . This leads to the same coefficient matrix $B^L = B^R$ for

linear systems for α^L and α^R and the same right-hand sides

$$\mathbf{b}^L = \mathbf{b}^R = \begin{cases} \frac{\partial f}{\partial x}(v_i), & 1 \leq i \leq 4 \\ \frac{\partial^2 f}{\partial x \partial y}(v_{i-4}), & 5 \leq i \leq 8 \\ \frac{\partial^2 f}{\partial x \partial z}(v_{i-8}), & 9 \leq i \leq 12 \\ \frac{\partial^3 f}{\partial x \partial y^2}(v_{i-12}), & 13 \leq i \leq 16 \\ \frac{\partial^3 f}{\partial x \partial y \partial z}(v_{i-16}), & 17 \leq i \leq 20 \\ \frac{\partial^3 f}{\partial x \partial z^2}(v_{i-20}), & 21 \leq i \leq 24 \\ \frac{\partial^4 f}{\partial x \partial y^2 \partial z}(v_{i-24}), & 25 \leq i \leq 28 \\ \frac{\partial^4 f}{\partial x \partial y \partial z^2}(v_{i-28}), & 29 \leq i \leq 32 \\ \frac{\partial^5 f}{\partial x \partial y^2 \partial z^2}(v_{i-32}), & 33 \leq i \leq 36 \end{cases} \quad (47)$$

Thus, $\alpha^L = \alpha^R$, which implies that $\frac{\partial \mathcal{P}^L}{\partial x}(1, y, z) = \frac{\partial \mathcal{P}^R}{\partial x}(0, y, z)$ and hence $\frac{\partial \mathcal{P}}{\partial x}$ is continuous on the boundary (v_1, v_3, v_4, v_2) . \square

Corollary 3.1. *The polynomial $\frac{\partial \mathcal{P}}{\partial s}$, $s \in \{x, y, z\}$ is continuous on mesh boundaries perpendicular to the s -axis.*

Proof. From **Lemma 3** $\frac{\partial \mathcal{P}}{\partial x}$ is continuous on the boundary (v_1, v_3, v_4, v_2) . The boundary is an arbitrary boundary perpendicular to the x -axis, thus $\frac{\partial \mathcal{P}}{\partial x}$ is continuous on any mesh boundary perpendicular to the x -axis. Then, by symmetry and **Lemma 3**, $\frac{\partial \mathcal{P}}{\partial y}$ and $\frac{\partial \mathcal{P}}{\partial z}$ are continuous on any mesh boundary perpendicular to the y and z -axes respectively. \square

Theorem 4 (Global \mathcal{C}^1 Continuity). *The triquintic interpolant \mathcal{P} is \mathcal{C}^1 continuous everywhere.*

Proof. From **Corollary 3.1**, and **Corollary 2.1**, the first derivatives of \mathcal{P} are continuous on any mesh boundary perpendicular to the x , y and z axes, thus \mathcal{P} is everywhere \mathcal{C}^1 continuous. \square

Lemma 5. *The derivatives*

$$\frac{\partial^2 \mathcal{P}}{\partial x \partial y} \text{ and } \frac{\partial^2 \mathcal{P}}{\partial x \partial z}$$

are continuous on mesh boundaries perpendicular to the x -axis.

Proof. From **Lemma 3** and **Corollary 3.1**, $\frac{\partial \mathcal{P}}{\partial x}$ is a polynomial in y and z and continuous on mesh boundaries perpendicular to the x -axis. Thus all derivatives in y and z are also continuous on these boundaries. Specifically, $\frac{\partial^2 \mathcal{P}}{\partial x \partial y}$ and $\frac{\partial^2 \mathcal{P}}{\partial x \partial z}$ are continuous on mesh boundaries perpendicular to the x -axis. \square

Corollary 5.1. *The derivatives*

$$\frac{\partial^2 \mathcal{P}}{\partial x \partial y} \text{ and } \frac{\partial^2 \mathcal{P}}{\partial y \partial z}$$

are continuous on mesh boundaries perpendicular to the y-axis and

$$\frac{\partial^2 \mathcal{P}}{\partial x \partial z} \text{ and } \frac{\partial^2 \mathcal{P}}{\partial y \partial z}$$

are continuous on mesh boundaries perpendicular to the z-axis.

Proof. The corollary follows from **Lemma 5** and symmetry. \square

Lemma 6. *The mixed second derivatives are globally continuous.*

Proof. **Lemma 2**, **Corollary 2.1**, **Lemma 5** and **Corollary 5.1** together prove that the mixed derivatives are continuous on all boundaries and hence are globally continuous. \square

Lemma 7. *The polynomial $\frac{\partial^2 \mathcal{P}}{\partial x^2}$ is continuous on the boundary (v_1, v_3, v_4, v_2) .*

Proof. The proof is similar to that for **Lemma 1** and **Lemma 3**. It is sufficient to show that $\frac{\partial^2 \mathcal{P}^L}{\partial x^2}(1, y, z) = \frac{\partial^2 \mathcal{P}^R}{\partial x^2}(0, y, z)$. Note that

$$\frac{\partial^2 \mathcal{P}}{\partial x^2}(x, y, z) = \sum_{j,k=0}^5 \sum_{l=1}^5 i(i-1)a_{ijk}x^{i-2}y^jz^k. \quad (48)$$

On the boundary,

$$\frac{\partial^2 \mathcal{P}^L}{\partial x^2}(1, y, z) = \sum_{j,k=0}^5 \left(\sum_{i=2}^5 i(i-1)a_{ijk} \right) y^jz^k = (\boldsymbol{\alpha}^L)^T \boldsymbol{\mu}^L, \quad (49)$$

where

$$\alpha_{1+j+6k}^L = \sum_{i=2}^5 i(i-1)a_{ijk}, \quad j, k = 0, 1, 2, 3, 4, 5, \quad (50)$$

and

$$\frac{\partial^2 \mathcal{P}^R}{\partial x^2}(0, y, z) = \sum_{j,k=0}^5 2a_{2jk} y^jz^k = (\boldsymbol{\alpha}^R)^T \boldsymbol{\mu}^R, \quad (51)$$

with

$$\alpha_{1+j+6k}^R = 2a_{2jk}, \quad j, k = 0, 1, 2, 3, 4, 5, \quad (52)$$

and

$$\mu_{1+j+6k}^L = \mu_{1+j+6k}^R = y^jz^k, \quad j, k = 0, 1, 2, 3, 4, 5. \quad (53)$$

Again, we have $\boldsymbol{\mu}^L = \boldsymbol{\mu}^R$, hence we only need to show that $\boldsymbol{\alpha}^L = \boldsymbol{\alpha}^R$. At the four vertices $\{v_1, v_2, v_3, v_4\}$, we enforce the following subset of the original set of constraints

$$\left. \begin{aligned} \frac{\partial^2 \mathcal{P}}{\partial x^2} &= \frac{\partial^2 f}{\partial x^2}, & \frac{\partial^3 \mathcal{P}}{\partial x^2 \partial y} &= \frac{\partial^3 f}{\partial x^2 \partial y}, & \frac{\partial^3 \mathcal{P}}{\partial x^2 \partial z} &= \frac{\partial^3 f}{\partial x^2 \partial z}, & \frac{\partial^4 \mathcal{P}}{\partial x^2 \partial y^2} &= \frac{\partial^4 f}{\partial x^2 \partial y^2}, & \frac{\partial^4 \mathcal{P}}{\partial x^2 \partial y \partial z} &= \frac{\partial^4 f}{\partial x^2 \partial y \partial z}, \\ \frac{\partial^4 \mathcal{P}}{\partial x^2 \partial z^2} &= \frac{\partial^4 f}{\partial x^2 \partial z^2}, & \frac{\partial^5 \mathcal{P}}{\partial x^2 \partial y^2 \partial z} &= \frac{\partial^5 f}{\partial x^2 \partial y^2 \partial z}, & \frac{\partial^5 \mathcal{P}}{\partial x^2 \partial y \partial z^2} &= \frac{\partial^5 f}{\partial x^2 \partial y \partial z^2}, & \frac{\partial^6 \mathcal{P}}{\partial x^2 \partial y^2 \partial z^2} &= \frac{\partial^6 f}{\partial x^2 \partial y^2 \partial z^2} \end{aligned} \right\}. \quad (54)$$

which involve a double derivative in x . This leads to the same coefficient matrix $B^L = B^R$ for linear systems for α^L and α^R and the same right-hand sides

$$\mathbf{b}^L = \mathbf{b}^R = \begin{cases} \frac{\partial^2 f}{\partial x^2}(v_i), & 1 \leq i \leq 4 \\ \frac{\partial^3 f}{\partial x^2 \partial y}(v_{i-4}), & 5 \leq i \leq 8 \\ \frac{\partial^3 f}{\partial x^2 \partial z}(v_{i-8}), & 9 \leq i \leq 12 \\ \frac{\partial^4 f}{\partial x^2 \partial y^2}(v_{i-12}), & 13 \leq i \leq 16 \\ \frac{\partial^4 f}{\partial x^2 \partial y \partial z}(v_{i-16}), & 17 \leq i \leq 20 \\ \frac{\partial^4 f}{\partial x^2 \partial z^2}(v_{i-20}), & 21 \leq i \leq 24 \\ \frac{\partial^5 f}{\partial x^2 \partial y^2 \partial z}(v_{i-24}), & 25 \leq i \leq 28 \\ \frac{\partial^5 f}{\partial x^2 \partial y \partial z^2}(v_{i-28}), & 29 \leq i \leq 32 \\ \frac{\partial^6 f}{\partial x^2 \partial y^2 \partial z^2}(v_{i-32}), & 33 \leq i \leq 36 \end{cases} \quad (55)$$

Thus, $\alpha^L = \alpha^R$, which implies that $\frac{\partial^2 \mathcal{P}^L}{\partial x^2}(1, y, z) = \frac{\partial^2 \mathcal{P}^R}{\partial x^2}(0, y, z)$ and hence $\frac{\partial^2 \mathcal{P}}{\partial x^2}$ is continuous on the boundary (v_1, v_3, v_4, v_2) . \square

Lemma 8. *The polynomial $\frac{\partial^2 \mathcal{P}}{\partial x^2}$ is continuous everywhere.*

Proof. **Lemma 7** shows that $\frac{\partial^2 \mathcal{P}}{\partial x^2}$ is continuous on faces perpendicular to the x -axis. **Corollary 2.1** shows that $\frac{\partial^2 \mathcal{P}}{\partial x^2}$ is continuous on faces perpendicular to the y and z -axis. Within a mesh element, \mathcal{P} is \mathcal{C}^∞ , thus $\frac{\partial^2 \mathcal{P}}{\partial x^2}$ is at continuous everywhere. \square

Theorem 9 (Global \mathcal{C}^2 Continuity). *The triquintic interpolant \mathcal{P} is \mathcal{C}^2 continuous everywhere.*

Proof. From **Lemma 8** and symmetry, $\frac{\partial^2 \mathcal{P}}{\partial x^2}$, $\frac{\partial^2 \mathcal{P}}{\partial y^2}$ and $\frac{\partial^2 \mathcal{P}}{\partial z^2}$ are continuous everywhere. And the mixed second derivatives are continuous everywhere, according to **Lemma 6**. Thus, \mathcal{P} has global \mathcal{C}^2 continuity! \square

4.2. Global \mathcal{C}^3 continuity does not hold

Lemma 10. *The triquintic interpolant \mathcal{P} is not \mathcal{C}^3 continuous everywhere.*

Proof. We prove by contradiction. Consider the interpolant along the x -axis ($y = z = 0$). Without loss of generality, we focus on two adjacent mesh elements on the interval $[0, 2]$ where the left mesh is on $[0, 1]$ and the right mesh is on $[1, 2]$. Define the left interpolant as

$$\mathcal{P}^L(x, 0, 0) = a_{000} + a_{100}x + a_{200}x^2 + a_{300}x^3 + a_{400}x^4 + a_{500}x^5, \quad (56)$$

and the right interpolant as

$$\mathcal{P}^L(x, 0, 0) = b_{000} + b_{100}x + b_{200}x^2 + b_{300}x^3 + b_{400}x^4 + b_{500}x^5. \quad (57)$$

The left and right interpolants are fully determined by the values of the function and its first and second derivatives in x at the endpoints of the intervals $[0, 1]$ and $[1, 2]$ respectively. We find that

$$a_{000} = f(0, 0, 0), \quad a_{100} = f_x(0, 0, 0), \quad a_{200} = \frac{1}{2}f_{xx}(0, 0, 0), \quad (58)$$

$$\begin{bmatrix} a_{300} \\ a_{400} \\ a_{500} \end{bmatrix} = \begin{bmatrix} 10 & -4 & 1/2 \\ -15 & 7 & -1 \\ 6 & -3 & 1/2 \end{bmatrix} \begin{bmatrix} f(1, 0, 0) - f(0, 0, 0) - f_x(0, 0, 0) - \frac{1}{2}f_{xx}(0, 0, 0) \\ f_x(1, 0, 0) - f_x(0, 0, 0) - f_{xx}(0, 0, 0) \\ f_{xx}(1, 0, 0) - f_{xx}(0, 0, 0) \end{bmatrix}, \quad (59)$$

$$b_{000} = f(1, 0, 0), \quad b_{100} = f_x(1, 0, 0), \quad a_{200} = \frac{1}{2}f_{xx}(1, 0, 0), \quad (60)$$

$$\begin{bmatrix} b_{300} \\ b_{400} \\ b_{500} \end{bmatrix} = \begin{bmatrix} 10 & -4 & 1/2 \\ -15 & 7 & -1 \\ 6 & -3 & 1/2 \end{bmatrix} \begin{bmatrix} f(2, 0, 0) - f(1, 0, 0) - f_x(1, 0, 0) - \frac{1}{2}f_{xx}(1, 0, 0) \\ f_x(2, 0, 0) - f_x(1, 0, 0) - f_{xx}(1, 0, 0) \\ f_{xx}(2, 0, 0) - f_{xx}(1, 0, 0) \end{bmatrix}. \quad (61)$$

Assume that the interpolant is \mathcal{C}^3 continuous everywhere. Then, specifically,

$$\frac{\partial^3 \mathcal{P}^L}{\partial x^3}(1, 0, 0) = \frac{\partial^3 \mathcal{P}^R}{\partial x^3}(0, 0, 0), \quad (62)$$

which implies that,

$$a_{300} + 4a_{400} + 5a_{500} = b_{300}. \quad (63)$$

From Equation (59),

$$\begin{aligned} a_{300} + 4a_{400} + 5a_{500} &= 10(f(1, 0, 0) - f(0, 0, 0)) \\ &\quad - 4f_x(0, 0, 0) - 6f_x(1, 0, 0) - \frac{1}{2}f_{xx}(0, 0, 0) + \frac{3}{2}f_{xx}(1, 0, 0), \end{aligned} \quad (64)$$

and from Equation (61),

$$b_{300} = 10(f(2, 0, 0) - f(1, 0, 0)) - 6f_x(1, 0, 0) - 4f_x(2, 0, 0) - \frac{19}{2}f_{xx}(1, 0, 0) + \frac{1}{2}f_{xx}(2, 0, 0). \quad (65)$$

Note that because the interpolant is \mathcal{C}^2 continuous everywhere,

$$a_{000} = b_{000}, \quad a_{100} = b_{100}, \quad \text{and} \quad a_{200} = b_{200}. \quad (66)$$

Then the consequence of Equations (58), (60) and (63) is that, for every interpolated function,

$$4(f_x(2, 0, 0) - f_x(0, 0, 0)) - \frac{1}{2}(f_{xx}(2, 0, 0) - 21f_{xx}(0, 0, 0)) = 10(f(2, 0, 0) - f(0, 0, 0)), \quad (67)$$

which is false. Thus, the triquintic is not globally \mathcal{C}^3 continuous. \square

5. Error analysis and numerical results

First, we prove that for the tricubic interpolant, the error decays quadratically and for the triquintic interpolant, the error decays cubically.

5.1. Error analysis

Lemma 11. *The error for the tricubic interpolant decays as a quadratic and the error for the triquintic interpolant decays as a cubic.*

Proof. Let $f(x, y, z) \in \mathcal{C}^\infty$ be the function to be interpolated. Then, the Taylor series for f centered at the origin $\mathbf{0} = (0, 0, 0)$ is

$$\begin{aligned} f(x, y, z) = f(\mathbf{0}) &+ f_x(\mathbf{0})x + f_y(\mathbf{0})y + f_z(\mathbf{0})z + \frac{1}{2}(f_{xx}(\mathbf{0})x^2 + f_{yy}(\mathbf{0})y^2 + f_{zz}(\mathbf{0})z^2) \\ &+ f_{xy}(\mathbf{0})xy + f_{xz}(\mathbf{0})xz + f_{yz}(\mathbf{0})yz \\ &+ \frac{1}{6}(f_{xxx}(\mathbf{0})x^3 + f_{yyy}(\mathbf{0})y^3 + f_{zzz}(\mathbf{0})z^3) + \dots \end{aligned} \quad (68)$$

Define the tricubic interpolant as

$$\mathcal{P}_3(x, y, z) = \sum_{i,j,k=0}^3 a_{ijk}x^i y^j z^k, \quad (69)$$

and the triquintic interpolant as

$$\mathcal{P}_5(x, y, z) = \sum_{i,j,k=0}^5 b_{ijk}x^i y^j z^k. \quad (70)$$

Apply the tricubic constraints given in Equation (4) at $(0, 0, 0)$ to compute a few coefficients of \mathcal{P}_3 . Similarly, apply the triquintic constraints in (9), (22), (23), (24) and (25) at $(0, 0, 0)$ to compute a few coefficients of \mathcal{P}_5 . We find that

$$a_{000} = b_{000} = f(\mathbf{0}), \quad (71)$$

$$a_{100} = b_{100} = f_x(\mathbf{0}), \quad a_{010} = b_{010} = f_y(\mathbf{0}), \quad a_{001} = b_{001} = f_z(\mathbf{0}), \quad (72)$$

$$a_{110} = b_{110} = f_{xy}(\mathbf{0}), \quad a_{101} = b_{101} = f_{xz}(\mathbf{0}), \quad a_{011} = b_{011} = f_{yz}(\mathbf{0}), \quad (73)$$

$$b_{200} = \frac{1}{2}f_{xx}(\mathbf{0}), \quad b_{020} = \frac{1}{2}f_{yy}(\mathbf{0}), \quad b_{002} = \frac{1}{2}f_{zz}(\mathbf{0}). \quad (74)$$

Then,

$$\mathcal{P}_3(x, y, z) = f(\mathbf{0}) + f_x(\mathbf{0})x + f_y(\mathbf{0})y + f_z(\mathbf{0})z + a_{200}x^2 + a_{020}y^2 + a_{002}z^2 + \dots \quad (75)$$

Note that the coefficient

$$a_{200} = 3f(1, 0, 0) - 3f(0, 0, 0) - 2f_x(0, 0, 0) - f_x(1, 0, 0), \quad (76)$$

which is not necessarily equal to $\frac{1}{2}f_{xx}(\mathbf{0})$. Similarly, a_{020} and a_{002} are not necessarily equal to $\frac{1}{2}f_{yy}(\mathbf{0})$ and $\frac{1}{2}f_{zz}(\mathbf{0})$ respectively. Thus, the error in a tricubic interpolation is given by

$$\begin{aligned} e_3(x, y, z) &= |f(x, y, z) - \mathcal{P}_3(x, y, z)|, \\ &= \left| \frac{1}{2}((f_{xx}(\mathbf{0}) - 2a_{200})x^2 + (f_{yy}(\mathbf{0}) - 2a_{020})y^2 + (f_{zz}(\mathbf{0}) - 2a_{002})z^2) + \dots \right|. \end{aligned} \quad (77)$$

Equation (77) shows that the tricubic error decays quadratically in x , y and z .

We follow similar arguments for the triquintic interpolant with,

$$\begin{aligned} \mathcal{P}_5(x, y, z) = f(\mathbf{0}) &+ f_x(\mathbf{0})x + f_y(\mathbf{0})y + f_z(\mathbf{0})z + \frac{1}{2}(f_{xx}(\mathbf{0})x^2 + f_{yy}(\mathbf{0})y^2 + f_{zz}(\mathbf{0})z^2) \\ &+ f_{xy}(\mathbf{0})xy + f_{xz}(\mathbf{0})xz + f_{yz}(\mathbf{0})yz + a_{300}x^3 + a_{030}y^3 + a_{003}z^3 + \dots \end{aligned} \quad (78)$$

Note that, Equation (15) and Equation (20), imply

$$a_{300} = 10(f(1, 0, 0) - f(0, 0, 0)) - 6f_x(0, 0, 0) - 4f_x(1, 0, 0) - \frac{3}{2}f_{xx}(0, 0, 0) + \frac{1}{2}f_{xx}(1, 0, 0), \quad (79)$$

which is not necessarily equal to $\frac{1}{6}f_{xxx}(\mathbf{0})$. Similarly, a_{030} and a_{003} are not necessarily equal to $\frac{1}{6}f_{yyy}(\mathbf{0})$ and $\frac{1}{6}f_{zzz}(\mathbf{0})$ respectively. Thus, the error in the triquintic interpolation is given by

$$\begin{aligned} e_5(x, y, z) &= |f(x, y, z) - \mathcal{P}_5(x, y, z)|, \\ &= \left| \frac{1}{6}((f_{xxx}(\mathbf{0}) - 6a_{200})x^3 + (f_{yyy}(\mathbf{0}) - 6a_{020})y^3 + (f_{zzz}(\mathbf{0}) - 6a_{002})z^3) + \dots \right|. \end{aligned} \quad (80)$$

From Equation (80), we see that the triquintic error decays as a cubic in x , y and z . \square

5.2. Numerical results

Figure 3 provides numerical evidence for **Lemma 11** for $f(x, y, z) = \frac{1}{\sqrt{x^2 + y^2 + z^2 + 0.1}}$ (top plot) and $g(x, y, z) = (x^2 + y^2 + z^2) \cdot e^{-(x^2 + y^2 + z^2)}$ (bottom plot). The absolute errors defined in Equations (77) and (80) are computed along the vector $\mathbf{r} = \gamma \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3} \right)$, where $\gamma = 0 : 0.001 : 0.1$. Figure 3 is a log-log plot of the errors vs $r = |\mathbf{r}|$. We see that the absolute error for the tricubic, $e_3(x, y, z)$, matches $y = C \cdot r^2$ to support the conclusion in Equation (77). Similarly, the triquintic absolute error, $e_5(x, y, z)$, matches $y = C \cdot r^3$, as predicted by Equation (80).

Figure 3 also shows that as expected, the triquintic interpolant is more accurate than the tricubic interpolant. Figure 4 provides further study of the comparative accuracy of the two interpolants. We plot the error for the interpolation of a function and its derivatives $\{\partial_x, \partial_{xy}, \partial_{xyz}\}$ at 50 randomly generated points in the unit cube. Results are provided for the same two functions, $f(x, y, z)$ (left column) and $g(x, y, z)$ (right column). As expected, triquintic interpolation provides higher accuracy for a function and its derivatives.

Table 1, compares the accuracy of the integrals of the interpolants for $f(x, y, z)$ and $g(x, y, z)$. We use MATLAB's in-built numerical quadrature function to compute $\int_{[0,1]^3} f \, d\mathbf{x}$ and $\int_{[0,1]^3} g \, d\mathbf{x}$. The integral for the interpolants are computed as

$$\int_{[0,1]^3} \mathcal{P} \, d\mathbf{x} = \sum_{i,j,k=0}^n \int_{[0,1]^3} a_{ijk} x^i y^j z^k \, d\mathbf{x} = \sum_{i,j,k=0}^n \frac{a_{ijk}}{(i+1)(j+1)(k+1)}, \quad (81)$$

where $n = 3$ for the tricubic and $n = 5$ for the triquintic. Table 1 shows that the triquintic approximation of the integrals is more accurate than the tricubic approximation.

Before we conclude, we note that as explained by Lekien and Marsden, even though the presentation has been focused on Cartesian grids, the development extends to rectilinear grids as well.

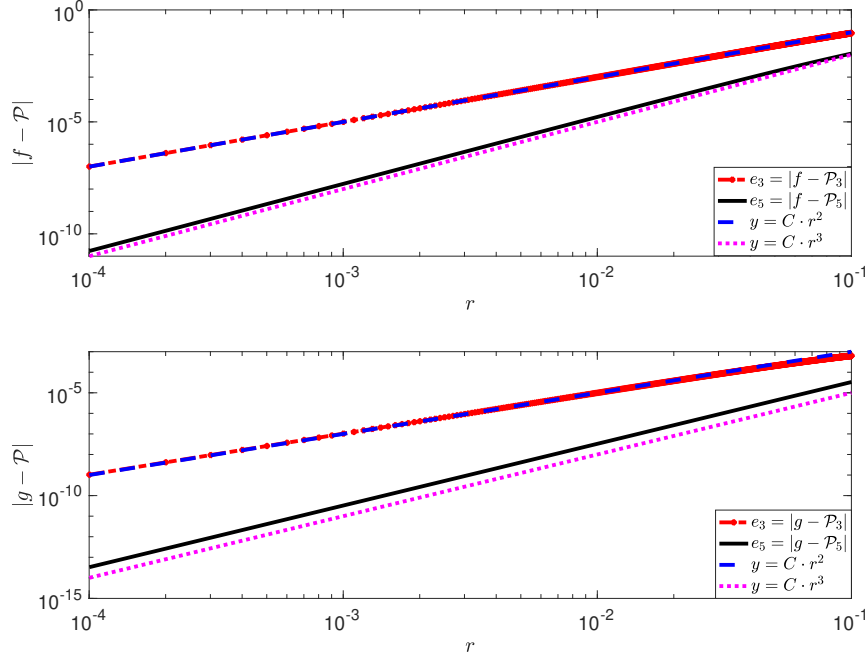


Figure 3: Numerical evidence for decay rate of the tricubic and triquintic interpolants. The top plot is for $f(x, y, z)$ and the bottom plot is for $g(x, y, z)$.

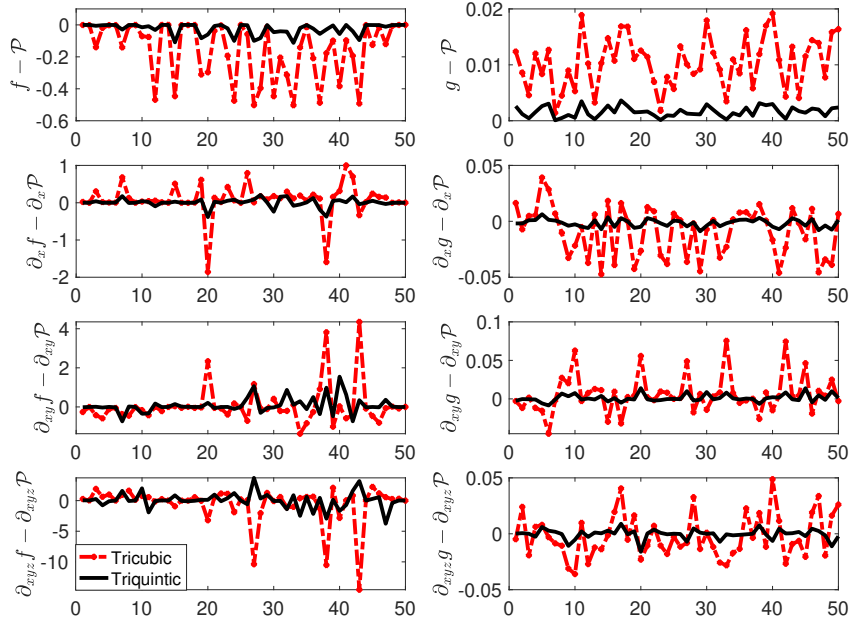


Figure 4: Comparison of the error in the tricubic and triquintic interpolants for 2 functions and their derivatives. The left column is for $f(x, y, z)$ and the right column is for $g(x, y, z)$.

Table 1: Accuracy of integrals of the interpolants

Interpolant	$\int_{[0,1]^3} f(\mathbf{x}) - \mathcal{P}(\mathbf{x}) \, d\mathbf{x}$	$\int_{[0,1]^3} g - \mathcal{P} \, d\mathbf{x}$
\mathcal{P}_3	0.128868208976672	0.010551038583430
\mathcal{P}_5	0.018646565877596	0.001756644668320

For a rectilinear mesh unit $[x_{\min}, x_{\max}] \times [y_{\min}, y_{\max}] \times [z_{\min}, z_{\max}]$, the mesh unit is mapped to the unit cube via the transformation

$$T(x, y, z) = \left(\frac{x - x_{\min}}{\Delta x}, \frac{y - y_{\min}}{\Delta y}, \frac{z - z_{\min}}{\Delta z} \right) = (\bar{x}, \bar{y}, \bar{z}), \quad (82)$$

where $\Delta x = x_{\max} - x_{\min}$, $\Delta y = y_{\max} - y_{\min}$ and $\Delta z = z_{\max} - z_{\min}$. Then, the triquintic interpolant is defined as

$$\mathcal{P}(x, y, z) = \sum_{i,j,k=0}^5 a_{ijk} \bar{x}^i \bar{y}^j \bar{z}^k. \quad (83)$$

The elements of the right-hand side vector \mathbf{b} defined in Equation (26) are scaled accordingly as

$$\Delta x^\beta \Delta y^\gamma \Delta z^\nu \frac{\partial^{\beta+\gamma+\nu} f}{\partial x^\beta \partial y^\gamma \partial z^\nu}, \quad \beta, \gamma, \nu \in \{0, 1, 2\}. \quad (84)$$

6. Conclusions

This paper developed an isotropic triquintic interpolant and proved that the interpolant is \mathcal{C}^2 continuous everywhere. The driver of the interpolation method is a 216×216 invertible matrix that relates the coefficients of the interpolant to the function and its derivatives at the eight corners of a unit cube mesh element. We proved that the method is not \mathcal{C}^3 continuous globally and that the error decays as a cubic. Numerical tests were provided to support the analysis of the convergence of the method. The advantages of the triquintic interpolant developed in this paper over the tricubic interpolant of Lekien and Marsden [9] are:

1. The triquintic is \mathcal{C}^2 everywhere and thus has higher smoothness while the tricubic is globally \mathcal{C}^1 .
2. The triquintic is more accurate than the tricubic for approximating function values.
3. The triquintic produces more accurate interpolation of higher order derivatives.

The disadvantage of the triquintic is that it requires up to 6th order derivatives of the interpolated function while the tricubic requires only up to 3rd order derivatives. Additionally, the tricubic matrix is 64×64 while the triquintic matrix is 216×216 . This disparity in matrix sizes will perhaps be an issue if the matrix-vector multiplication has to be done many times. However, the best use case for both interpolants is when several values inside the unit cube need to be interpolated. Then the coefficients of the interpolant are computed once by Equation (5) and used repeatedly to interpolate all the needed values. In this case, the difference in computational cost between the tricubic and triquintic interpolants are negligible.

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