4th IM-Workshop on

Applied Approximation, Signals and Images

Bernried (Germany)
March 4–8, 2019

ABSTRACTS

Organizers:
- Costanza Conti
- Mariantonia Cotronei
- Nira Dyn
- Brigitte Forster
- Tomas Sauer

PROGRAM

Monday, March 4	
09:30– 09:40	*Welcome & Opening*
09:40–10:50	Getting to know each other: Mathematical speed dating I
10:50–11:20	**Coffee break**
11:20–12:30	Getting to know each other: Mathematical speed dating II
15:00–15:30	**Coffee & cake**
15:30–16:30	Dmitry Batenkov: *Stability of some super-resolution problems*
16:30–17:30	Benedikt Diederichs: *Localizing Functions and the Stability of Sparse Frequency Estimation*
Tuesday, March 5	
09:00–09:30	Maria Charina: *Hermite subdivision and tight wavelet frames*
09:30–10:30	Ognyan Kounchev: *Polyharmonic Interpolation, subdivision, and Daubechies type wavelets*
10:30–11:00	**Coffee break**
11:30–12:00	Ulrich Reif: *Geometric Hermite Subdivision*
12:00–12:30	Sergio López-Ureña: *Non-linear subdivision schemes and exponential polynomials*
15:00–15:30	**Coffee & cake**
15:30–16:00	Svenja Hüning: *Towards subdivision in* all *manifolds: Case-study on the sphere*
16:00–16:30	A. Michael Stock: *Wavelets and Applications in Computed Tomography*
Wednesday, March 6	
09:00–90:30	Michael Skrzipek: *Connections between the Prony Polynomial and Some Orthogonal Polynomials*
09:30–10:30	Thomas Mejstrik: *Modified invariant polytope algorithm and t-toolboxes for Matlab*
10:30–11:00	**Coffee break**
11:00–11:30	Aleš Vavpetič: *A Remes type algorithm for geometric approximation of a circular arc*
11:30–12:00	Emil Žagar: *Arc length preserving approximation by planar Pythagorean-hodograph curves*
12:00–12:30	Kai Hormann: *Quartic Bézier curves with rational offsets*
	Excursion
Thursday, March 7	
09:00–09:30	Jan Grošelj: *Smooth cubic Powell–Sabin B-splines on three-directional triangulations*
09:30–10:00	Hendrik Speleers: *Quasi-interpolation with cubic Powell–Sabin splines*
10:00–10:30	Espen Sande: *Sharp error estimates for spline approximation*
10:30–11:00	**Coffee break**
11:00–11:30	Florian Martin: *Trimmed NURBS Surfaces with Low Degree Boundary*
11:30–12:00	Francesco Dell'Accio: *On the Hexagonal Shepard method*
12:00–12:30	Filomena Di Tommaso: *Functional and derivative data interpolation by triangular Shepard operators*
15:00–15:30	**Coffee & cake**
15:30–16:00	A. Michael Stock: *Wavelets and Applications in Computed Tomography*
15:30–16:00	Peter Massopust: *Some Remarks about B-Splines as Functions of Order*
16:00–16:30	Dörte Rüweler: *3d data acquisition and printing*
Friday, March 8	
09:00–09:30	*Packing and paying*
09:30–10:30	Tomas Sauer: *Generalized convolutions and Hankel operators*
10:30–11:00	**Coffee break**
11:00–11:30	Costanza Conti: *Smoothing exponential splines for Laplace transform inversion of multiexponential decay data*
11:30–12:00	Mariantonia Cotronei: *Orthogonal (multi)wavelets and system theory*
12:00–12:05	*Closing remarks*

Stability of some super-resolution problems

Dmitry Batenkov (Massachusetts Institute of Technology)

The problem of computational super-resolution asks to recover fine features of a signal from inaccurate and bandlimited data, using some kind of a-priori model as a regularization. I will describe several situations for which sharp bounds for stable reconstruction are known, depending on signal complexity, noise/uncertainty level, and available data bandwidth. I will also discuss optimal recovery algorithms, and some open questions.

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Hermite subdivision and tight wavelet frames

Maria Charina (University of Vienna, Austria), Nicolai Pastoors and Joachim Stöckler*

Surprisingly, construction of tight wavelet frames via the system theory approach leads to constructions of Hermite subdivision schemes. Such Hermite subdivision schemes generate matrix-valued basic limit functions and their matrix-valued subdivision symbols are contractive on the torus.

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Smoothing exponential splines for Laplace transform inversion of multiexponential decay data

Costanza Conti (Università di Firenze), Rosanna Campagna, Salvatore Cuomo*

In this talk we discuss the definition of a spline model to represent (multi)exponential decay data. Many applications are indeed based on data that behave asymptotically in this way, for example when the relationship between experimental data and their source is expressed in integral form and a Laplace transform inversion is needed. We define a piecewise smoothing exponential-spline represented by elements from the null spaces of differential operators tailored to represent exponential decay data. To reduce the condition number of the linear system to be solved to compute this spline, B-spline like functions are defined on the same spaces and locally represented by Bernstein-like bases that make easy Hermite interpolation conditions.

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Orthogonal (multi)wavelets and system theory

Mariantonia Cotronei (Università Mediterranea di Reggio Calabria), Maria Charina, Costanza Conti, Mihai Putinar*

Since the early eighties a variety of constructions of orthogonal scalar-, vector-, and matrix-valued wavelets has been proposed. We unify all those constructions. In fact, classical results from system theory and basic linear algebra allow us to show that there are no intrinsic differences between the elegant construction of scalar-valued wavelets by Daubechies or any other construction in the vector or matrix case. Our approach provides a way to parametrize all classes of possible wavelet and multi-wavelet filters together with the filters of the corresponding refinable functions.

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On the Hexagonal Shepard method

Francesco Dell'Accio (Università della Calabria), Filomena Di Tommaso*

The problem of Lagrange interpolation of functions of two variables by quadratic polynomials based on nodes which are vertices of a triangulation has been recently studied and local six-tuples of vertices which assure the uniqueness and the optimal-order of the interpolation polynomial are known. Following the idea of Little and the theoretical results on the approximation order and accuracy of the triangular Shepard method, we introduce an hexagonal Shepard operator with quadratic precision and cubic approximation order for the classical problem of scattered data approximation without least square fit.

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Localizing Functions and the Stability of Sparse Frequency Estimation

Benedikt Diederichs (University of Passau/Fraunhofer EZRT)

Estimating the frequencies of signals that are sparse in the frequency domain has attracted a lot of attention in the last few years. The catch is that for such signals it is possible to overcome the natural resolution limit, which is why such methods are sometimes called super-resolution methods.

It is, however, difficult to pin down stability properties of that problem. We give a fairly general stability result, independent of the method used, and derive a posteriori estimates. A main tool are special functions, which allow to estimate objects localized in the spatial domain by something localized in the frequency domain, and therefore overcoming the uncertainty principle.

If time permits, we comment on higher dimensional results as well as other mathematical problems where these functions pop up (like sphere packing or eigenvalue estimates of kernel matrices).

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Functional and derivative data interpolation by triangular Shepard operators

Filomena Di Tommaso (Università della Calabria), Francesco Dell'Accio, Otheman Nouisser, Benaissa Zerroudi*

In this talk we provide a solution to the Hermite interpolation problem for scattered data by means of fast and accurate algorithms. The proposed method is based on Little's basis functions and Hermite interpolant on the simplex by Sturm and an improvement which uses derivatives up to the order 2. The main advantage of the method is achieving approximation of order of $O(h^3)$ ($O(h^4)$ if derivatives of order 2 are provided) demonstrated both by theoretical and numerical results.

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Smooth cubic Powell–Sabin B-splines on three-directional triangulations

Jan Grošelj (University of Ljubljana), Hendrik Speleers*

The construction of smooth piecewise polynomial functions of low degrees on general triangulations has shown to be a challenging problem. Its complexity originates from the fact that a small change in geometry of the triangulation can have an impact on degrees of freedom of the spline function. There has been numerous attempts to isolate this problem, among which are preliminary refinements of the triangulation (with e.g. Clough–Tocher or Powell–Sabin splits), increased smoothness in parts of the domain, rational blending, or simply restrictions to special classes of triangulations.

In this talk we consider many of the aforementioned techniques in order to shape a smooth cubic precision spline space suitable for approximation and not too complex to analyze. We start with a set of C^1 cubic B-spline functions defined on a Powell–Sabin 6-refinement of the triangulation, which has been recently developed in [1], and investigate which additional smoothness properties these functions posses if we restrict ourselves to three-directional triangulations, i.e. triangulations generated by three linearly independent vectors summing to zero. We show that with a recombination of the B-splines it is possible to obtain a basis for a C^1 spline space with C^2 smoothness on every triangle of the original triangulation. Furthermore, we discuss some nice properties of the spline representation in terms of these new basis functions, including subdivision with convex weights after dyadic refinement.

References

[1] J. Grošelj and H. Speleers. *Construction and analysis of cubic Powell–Sabin B-splines.* Comput. Aided Geom. Design 57, 1–22, 2017.

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Quartic Bézier curves with rational offsets

Kai Hormann (Università della Svizzera italiana), Jianmin Zheng*

This talk is about planar properly-parameterized, regular quartic Bézier curves that have rational offsets. Such curves are either Pythagorean hodograph (PH) or indirect Pythagorean hodograph (iPH) curves, and they include all quadratic curves, cubic PH curves, and cubic iPH curves as special cases. We give a complete analysis of these curves and derive their algebraic and geometric characterizations. The characterizations are given in terms of quantities related to the Bézier control polygon of the curves. Based on the derived characterizations, several geometric construction algorithms using quartic curves with rational offsets are presented as applications.

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Towards subdivision in *all* manifolds: Case-study on the sphere

Svenja Hüning (Graz University of Technology)

Algorithms producing limit curves by refining a given set of ordered points lying in a linear space are called subdivision schemes. They are well-studied with respect to convergence and smoothness. Adapted versions of such refinement rules have also been considered for data in nonlinear spaces, like Riemannian manifolds.
There are convergence results which can be applied to all manifolds. However, those results which make use of the so-called proximity conditions are restricted to 'dense enough' input data. Additionally, one can extend linear subdivision schemes to manifolds with nonnegative sectional curvature with the Riemannian analogue. In this case, one obtains convergence results for *all* input data.
In this talk, we discuss ideas how to extend the previous results to manifolds with positive sectional curvature. In particular, we present suggestions how to use the Riemannian analogue of a subdivision scheme on the unit sphere.

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Polyharmonic Interpolation, subdivision, and Daubechies type wavelets

Ognyan Kounchev (Bulgarian Academy of Sciences)

We report about a multivariate approach to subdivision based on polyharmonic interpolation. The main role of interpolant is played by polyharmonic functions and the initial data are given on parallel lines (see [1]). We define a multivariate analog to the Deslaurier-Dubuc scheme, we introduce a polyharmonic subdivision scheme which reproduces polyharmonic functions of a given order p. Following the standard scheme explained in [1], by means of Fourier transform in one direction the polyharmonic functions are decomposed into an infinite number of one-dimensional exponential polynomials of a special kind. The interesting phenomenon is that the stationary polyharmonic subdivision is reduced to infinitely many non-stationary. Accordingly, using these one-dimensional non-stationary subdivisions we produce one-dimensional wavelets of Daubechies type, provided in [2]. Related subtle problems of interpolation by polyharmonic functions have been studied in detail in [3].

References

[1] O. Kounchev, Multivariate Polysplines. Application to Numerical and Wavelet Analysis, Academic Press-Elsevier, 2001.

[2] N. Dyn, O. Kounchev, D. Levin, H. Render, Regularity of generalized Daubechies wavelets reproducing exponential polynomials, Applied and Computational Harmonic Analysis, Volume 37, Issue 2, September 2014, Pages 288-306.

[3] O. Kounchev, H. Render, Interpolation of data functions on parallel hyperplanes, submitted.

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Non-linear subdivision schemes and exponential polynomials

Sergio López-Ureña (Universitat de València), Tomas Sauer*

A subdivision scheme S reproduces a space of functions $\mathcal{V}$, if for all $F \in \mathcal{V}$ the application of S to the sequence $F|_{\mathbb{Z}^s} := (F(\alpha))_{\alpha\in\mathbb{Z}^s}$ gives more evaluations of F at a finer grid, $SF|_{\mathbb{Z}^s} = F_{\Xi^{-1}\mathbb{Z}^s}$, where Ξ is the dilation matrix of S. We can find in the literature [1, 2] some results about sufficient and necessary conditions for reproduction provided that the subdivision scheme is linear. However, there is no result for the non-linear case, which has proven to be useful in some applications [3, 4].

We search for sufficient and necessary conditions in the non-linear case. We show that a stronger condition than reproduction should be considered, the *offset reproduction*, which is defined as

$$S\,(f + F|_{\mathbb{Z}^s}) = Sf + F_{\Xi^{-1}\mathbb{Z}^s}, \qquad \forall f \in \ell_\infty(\mathbb{Z}^s),\ \forall F \in \mathcal{V}.$$

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[2] N. Dyn, D. Levin, and A. Luzzatto. Exponentials reproducing subdivision schemes. *Foundations of Computational Mathematics*, 2003.

[3] R. Donat, S. López-Ureña and M. Santágueda. A family of non-oscillatory 6-point interpolatory subdivision schemes. *Advances in Computational Mathematics*, 2017.

[4] R. Donat and S. López-Ureña. Nonlinear stationary subdivision schemes that reproduce trigonometric functions. *arXiv:1809.03731*, 2018.

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Trimmed NURBS Surfaces with Low Degree Boundary

Florian Martin (Technische Universität Darmstadt), Ulrich Reif*

The trimming procedure is one of the most important techniques in Computer Aided Geometric Design to construct complex geometries. However, Non-Uniform Rational B-Splines (NURBS) surfaces as the standard modeling tool in the industry do not provide a natural way of adapting their visualization while maintaining the parametrization and mathematical description. In particular non continuous contacts to neighboring patches lead to gaps and overlaps that have to be dealt with manually.
In this talk, we present a novel method to represent G1 and even G2 continuous composite surfaces. As our description provides compatibility with the IGES and STEP file exchange formats, its application is highly recommended in the industrial design process.

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Some Remarks about B-Splines as Functions of Order

Peter Massopust (Technical University of Munich)

B-splines of complex order z can be considered as bivariate functions of the form $B : \mathbb{R} \times \mathbb{C}_{>1} \to \mathbb{C}$,

$$B(x, z) := \frac{1}{\Gamma(z)} \sum_{k=0}^{\infty} (-1)^k \binom{z}{k} (x-k)_+^{z-1},$$

where $\mathbb{C}_{>1} := \{z \in \mathbb{C} : \mathrm{Re} z > 1\}$.

In this short talk, we present some properties of $B(x, z)$ for fixed $x \in \mathbb{R}$. Those include the asymptotic behavior as $|\mathrm{Re}\, z| \to \infty$ and $|\mathrm{Im}\, z| \to \infty$, and the number and location of real zeros.

(The material presented is part of the Master's Thesis of Ludwig Bayer: *Holomorphic Properties of Complex B-Splines*, TUM, 2017.)

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Modified invariant polytope algorithm and t-toolboxes for Matlab

Thomas Mejstrik (University of Vienna),*

In several papers of 2013 – 2016, Guglielmi and Protasov made a breakthrough in the problem of the joint spectral radius computation, developing the invariant polytope algorithm which for most matrix families finds the exact value of the joint spectral radius. This algorithm found many applications in problems of functional analysis, approximation theory, combinatorics, etc.. We propose several modifications for the algorithm, making it roughly 3 times faster and suitable for higher dimensions. We present our user friendly implementation of the modified invariant polytope algorithm in Matlab and discuss its properties. Moreover, we present our Matlab toolbox for multiple subdivision schemes, which among other features offers the possibility to compute/estimate the exact Hölder regularity of subdivision.

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Geometric Hermite Subdivision

Ulrich Reif (Technische Universität Darmstadt), Andreas Weinmann*

We suggest subdivision schemes for geometric Hermite data, composed of points, tangent vectors, and optionally curvature values. Reproducing circles and clothoids, the schemes generate tidy results even in a vicinity of inflection points. The limit curves are proven to be G^1 or even G^2.

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3D data acquisition and printing

Dörte Rüweler (University of Passau)

Digitization of real world objects is an important topic in various applications, from reverse engineering and measurement to perservation of cultural heritage. The technologies for that purpose vary widely in cost and general availability.

Once an object is digitized, it can be modified and eventually be produced again, nowadays mostly by means of additive manufacturing, also known as 3D printing.

The talk gives a quick introduction to some of the technologies and in particular reports on our experiences with a filament printer, the most available technology due to its relatively low cost.

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Sharp error estimates for spline approximation

Espen Sande (University of Oslo), Carla Manni and Hendrik Speleers*

In this talk we give a priori error estimates in standard Sobolev norms for approximation in spline spaces of maximal smoothness on arbitrary grids. The error estimates are expressed in terms of a power of the maximal grid spacing, an appropriate derivative of the function to be approximated, and an explicit constant. Special attention is paid to the periodic case where we prove that the obtained constant is sharp. The results of this talk can be used to theoretically explain the benefits of spline approximation under k-refinement by isogeometric discretization methods. They also form a theoretical foundation for the outperformance of smooth spline discretizations of eigenvalue problems that has been numerically observed in the literature, and for optimality of geometric multigrid solvers in the isogeometric analysis context.

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Generalized convolutions and Hankel operators

Tomas Sauer (University of Passau/Fraunhofer IIS)

Given a nonsingular matrix $\Xi \in \mathbb{Z}^{s\times s}$, one can consider *generalized convolutions* that act on bi–infinite sequences $c, d : \mathbb{Z}^s \to \mathbb{R}$ as

$$c *_\Xi d = \sum_{\alpha\in\mathbb{Z}^s} c(\cdot + \Xi\alpha),\ d(\alpha)$$

and study the associated operators. This covers a lot of well known operations, in particular correlation ($\Xi = I$) and Hankel operators, convolution ($\Xi = -I$) and Toeplitz operators and, of course, subdivision operators where Ξ is an arbitrary *expansive matrix*, i.e., all eigenvalues are > 1 in modulus.

The particular interest of the talk consists in studying kernels and preservation properties of these operators and, as could be expected, their close connection to *Prony's problem*. This is not surprising since all these questions are related to *exponential polynomials*.

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Connections between the Prony Polynomial and Some Orthogonal Polynomials

Michael Skrzipek (Fernuniversität in Hagen)

We consider the reconstruction of frequencies $\omega_j \in [-\alpha, 0] + \mathrm{i}\,(-\pi, \pi]$, $\alpha \geq 0$, of a signal h from given samples, where h has the form

$$h(x) = \sum_{j=1}^{m} \lambda_j e^{\omega_j x}\ , \quad m < \infty, \quad \omega_i \neq \omega_j \text{ for } i \neq j, \quad \lambda_j \in \mathbb{C}\backslash\{0\}.$$

As is known, $z_j := e^{\omega_j}$ are the zeros of the so called Prony polynomial ρ_m. Characteristics of h reflect in properties of ρ_m and vice versa. We show that in this context orthogonal polynomials arise in a natural manner and can be used to calculate the frequencies or to infer on properties of the signal.

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Quasi-interpolation with cubic Powell–Sabin splines

Hendrik Speleers (University of Rome Tor Vergata), Jan Grošelj*

The process of constructing bivariate polynomial splines on triangulations can be simplified by applying a Powell–Sabin refinement to a general triangulation. Recently, C^1 cubic splines on Powell–Sabin triangulations with and without additional smoothness constraints have been considered for possible use in approximation theory and geometric modelling. Also, a stable B-form for such splines, which is based on local basis functions that form a convex partition of unity, has been provided [1]. This B-form is particularly interesting because it allows a representation of classical C^1 quadratic Powell–Sabin splines and C^1 cubic Clough–Tocher splines in a unified context.

In this talk we make use of the cubic Powell–Sabin B-form to introduce a general framework of methods for constructing quasi-interpolation operators based on local polynomial approximation [2]. We assign a linear functional to each basis function to specify the coefficients in the B-form. The functionals have a standard form, i.e., they take a cubic polynomial and evaluate it using the blossoming principle. Using this approach, a quasi-interpolation operator can be defined by providing a collection of cubic polynomials, which can be constructed based on local data sites through any standard approximation method, e.g., Lagrange or Hermite interpolation, least square approximation, etc. We study the properties of such quasi-interpolation operators and present general recipes to specify them in a way that they have a global or local polynomial precision and satisfy certain additional smoothness constraints. Finally, we derive some concrete methods and compare them with numerical experiments.

References

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[2] J. Grošelj and H. Speleers. *Three recipes for quasi-interpolation with cubic Powell–Sabin splines.* Comput. Aided Geom. Design 67, 47–70, 2018.

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Wavelets and Applications in Computed Tomography

A. Michael Stock (University of Passau), Benedikt Diederichs, Tomas Sauer*

Computed Tomography (CT) is an X-ray-based technique to generate three-dimensional datasets from real-world objects. Applications can be found in the manufacturing industry, medical imaging, and cultural heritage projects. Today, there exist CT devices that are able to create volumetric datasets of even hundreds of gigabytes in size.

To make that amount of data manageable, we present a wavelet-based method using the natural sparsity of the given CT scans when transforming the data into the wavelet domain. This approach takes advantage of the fact that the input data is mostly locally homogeneous with smooth boundaries, at least in industrial applications. Then, we briefly discuss coefficient thresholding techniques and related minimization problems, a wavelet-based edge detection method, and error estimates. To conclude, we give an outlook on how to directly reconstruct CT scans in the wavelet domain.

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A Remes type algorithm for geometric approximation of a circular arc

Aleš Vavpetič (University of Ljubljana), Emil Žagar*

A new algorithm for the construction of parametric polynomial approximants of circular arcs will be considered. It is based on the minimization of a particular error function, such as the radial distance or the simplified radial distance. The main step of the algorithm is the identification of the optimal zeros of the error function which is done by a kind of bisection method and can be also viewed as a Remes type algorithm. The approach leads to the construction of parametric polynomial approximants of a particular geometric smoothness. In this talk some low degree cases will be presented in detail and possible generalizations will be proposed.

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Arc length preserving approximation by planar Pythagorean-hodograph curves

Emil Žagar (University of Ljubljana and Institute of mathematics)

Interpolation of planar geometric data, such as positions, tangent directions and curvatures by parametric polynomial curves is a standard and well studied problem. However, there is not much known about interpolation of some additional global geometric data, such as the arc length, the bending energy,...We shall consider some particular problems involving interpolation of the arc length. Pythagorean-hodograph curves will be used.

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