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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The notion of super splines and vertex splines is introduced and studied. Quasi-interpolation formulas for real-time applications are constructed. The method of noncommutative blending of quasi-interpolation and vertex spline interpolation is introduced to yield interpolation schemes which are local, flexible, and of optimal approximation orders. These formulas can be applied to real-time interpolation by means of table-look-up or FIR implementation. Applications to engineering problems such as parallel implementation of the extended Kalman filter and Hankel-norm frequency domain methods are studied. Wavelets are constructed by applying cardinal splines, and hence, they are readily available for real-time interpolation and orthogonal wavelet decompositions and reconstructions.			
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18. Cont

wavelet orthogonal decompositions and reconstructions

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**Mathematical Methods and Algorithms for
Real-Time Applications**

FINAL REPORT

CHARLES K. CHUI
Texas A&M University
College Station, TX 77843-3368

September 25, 1990

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I. List of manuscripts submitted or published under SDIO/IST - ARO sponsorship

Books

1. Kalman Filtering with Real-Time Applications, (with G. Chen), Springer Series in Information Sciences # 17, Springer-Verlag, 1987. (Second edition in preparation)
2. Linear Systems and Optimal Control, (with G. Chen), Springer Series in Information Sciences # 18, Springer-Verlag, 1988.
3. Multivariate Splines, CBMS-NSF Series in Applied Mathematics # 54, SIAM, Philadelphia, 1988.

Papers

1. Image reconstruction by bivariate quadratic splines, (with A.K. Chan and K.B. Chan), IEEE Trans, ASSP, Vol. 36 (1988), 1525-1529.
2. A natural formulation of quasi-interpolation by multivariate splines, (with H. Diamond), Proc. Amer. Math. Society. Vol. 99 (1987), 643-646.
3. Interpolation by multivariate splines, (with H. Diamond and L.A. Raphael), Math. Comp., Vol. 51 (1988), 203-218.
4. On multivariate vertex splines and applications, (with M.J. Lai), in *Topics in Multivariate Approximation*, Academic Press, N.Y., 1987, pp.19-36.
5. Bivariate C^1 quadratic finite elements and vertex splines, (with T.X. He), Math. Comp, Vol. 54, No. 189 (1990), 169-187.
6. Shape-preserving Quasi-interpolation and interpolation, (with H. Diamond and L.A. Raphael), J. Comp. and Appl. Math., Vol. 25 (1989) 169-198.
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8. Multivariate vertex splines and finite elements, (with M.J. Lai), J. Approx. Theory, Vol. 60, No. 3 (1990), 245-343.
9. On bivariate super vertex splines, (with M.J. Lai), Constr. Approx. Vol. 6 (1990), 399-419.
10. Modified extended Kalman filtering and a real-time parallel algorithm for system parameter identification, (with G. Chen and H.C. Chui), IEEE Trans. Auto Cont, Vol. 35, No. 1 (1990), 100-104.
11. System reduction via truncated Hankel matrices, (with X. Li and J.D. Ward), Math. of Control, Signals, and Systems. To appear.
12. On the dimension of bivariate superspline spaces, (with T.X. He), Math. Comp. Vol. 53 (1989), 219-234.
13. On the convergence of s -numbers of compact Hankel operators, (with X. Li and J.D. Ward), CAT Report #184, Circuits, Systems, and Signal Processing. To appear.
14. Approximation and interpolation formulas for real-time applications, (with H. Diamond), Trans. of the 7th Army Conference on Appl. Math. and Computing, 1989, 765-772.
15. Vertex splines and their applications to interpolation of discrete data, in *Computation of Curves and Surfaces*, Ed. by W. Dahmen, M. Gasca, and C.A. Micchelli, Kluwer Academic Publishers, 1990, 137-181.

16. Rate of uniform convergence of rational functions corresponding to best approximants of truncated Hankel operators, (with X. Li and J. D. Ward), Math of Control, Signals, and Systems. To appear.
17. Construction and applications of interpolation formulas, in *Multivariate Approximation and Interpolation*, Ed. by W. Haussmann and K. Jetter, ISNM Series in Math., Birkhäuser Verlag Basel, 11-23.
18. Solution of the four-block problem via minimum-norm interpolation, (with X. Li), CAT Report #214.
19. A characterization of multivariate quasi-interpolation formulas and its applications, (with H. Diamond), Num. Math, Vol. 57 (1990), 105-121.
20. A general framework for local interpolation, (with H. Diamond), CAT Report #190, Texas A&M University, Numer. Math. To appear.
21. A cardinal spline approach to wavelets, (with J. Z. Wang), CAT Report #211.
22. On compactly supported spline wavelets and a duality principle, (with J. Z. Wang), CAT Report #213.
23. A general study of maximal robust stability regions, (with H.N. Mhaskar), Circuits, Systems, and Signal Processing. To appear.
24. Radial basis function approach to interpolation of large reflecting surface, (with A. K. Chan and L. T. Guan), in SPIE Vol. 1251 *Curves and Surfaces in Computer Vision and Graphics*, (L. A. Ferrari and R. J. P. de Figueiredo, Eds.), 1990, 62-72.
25. Application of generalized vertex splines to boundary element method for electromagnetic scattering, (with A. K. Chan and T. X. He), in 6th Annual Review of Progress in Applied Computational Electromagnetic Society, 1990, 329-337.
26. On multivariate robust stability, (with H. N. Mhaskar), CAT Report #216.
27. Curve design and analysis using splines and wavelets, Proc. 8th Army Conf. on Appl. Math. and Computing, June 1990. To appear.

II. Participating scientific personnel

Faculty

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G. Chen (Ph. D. awarded, Aug. 1987)

D. Duan

T.X. He (Ph. D. expected, May 1991)

M.J. Lai (Ph. D. awarded, Aug. 1989)

X. Li (Ph. D. expected, May 1991)

Q. Liu

J. Wang

Computer programmers (Undergraduate students)

Scott Bowers

Susan Fojtasek

III. Brief outline of research findings

The objective of this report is to give a very brief summary of the research findings on the project under Contract Number DAAL O3-87-K-0025 sponsored by SDIO/IST and managed by the U.S. Army Research Office. Technical details are not included since most of them have been reported as semi-annual progress reports. This project covered the period February 1, 1987 - July 30, 1990 which includes a six-month extension at no cost. The list of publications in Section I, page 1 - page 2, will also be used as references. Other references are listed at the end of this summary. We divide our results into five categories as follows:

1. Super splines and vertex splines.

Our results in this area are found in [4,5,8,9] with applications to interpolation to be discussed in the next section and other applications in Section 4. It is well known that every spline function in one variable can be represented as a B -spline series. However, with only a few exceptions, this nice local representation does not generalize to bivariate, and more generally multivariate, splines. One of the reasons is that the C^r piecewise polynomial functions on a triangulation have very complicated local structures, and the one that is crucial to the computational aspects is the extra free parameters on lower-dimensional manifolds that constitute the triangulation. This phenomenon is probably well known to some of the finite element people. In our work [4], we introduced the notion of **super splines** in order to drop the "useless" parameters. For instance, a C^1 quintic bivariate piecewise polynomial is restricted to be C^2 at the vertices. In our paper [9], we considered the smallest subspace of super splines in S_{3r+2}^r (i.e. C^r piecewise bivariate polynomials with total degree $3r + 2$) and showed that the approximation order is full, that is $3r + 3$ as shown in de Boor - Höllig [S1]. In fact, this super spline subspace has a basis consisting of vertex splines; and hence, a spline series representation is obtained. The notion of vertex splines was introduced by Chui and Lai in [S9]. Later development of super and vertex splines can be found in [5,8,9] and recent work of Alfeld, Höllig, Ibrahim, Piper, Schumaker, and others (cf. the articles in [S10,S12,S13,S28] and references therein).

2. Quasi-interpolation and interpolation formulas.

The central theme in this area of research is construction of "real-time" interpolation formulas, and real-time implementation of such formulas. In our work [2,3], we developed local quasi-interpolation schemes by introducing the so-called "Neumann-series" approach. Here, quasi-interpolation means optimal-order local linear approximation. In [19], we gave a complete characterization of all quasi-interpolation formulas. The most important application in [19] is construction of quasi-interpolation using arbitrary sample points and various data information. To change quasi-interpolation to actual local interpolation, preserving the optimal order of approximation, we introduced in [14,20] a (noncommutative) "blending" method by using vertex splines or generalized vertex splines. The emphasis is localness and optimality of the order of approximation. Hence, "table-look-up" can be used for real-time interpolation; or equivalently, an FIR (moving-average) scheme can be implemented. The general theory is extended to nonuniform grid and an application to solving nonlinear PDE's is discussed in [17], and many other applications and examples are included in my tutorial article [15], written for the NATO Graduate Studies on "Computations of Curves and Surfaces". In our work [6,7], we studied interpolation formulas

that preserve the shapes of the data. In particular, an almost real-time method is given in [6], and a comprehensive study on shape-criteria is given in [7].

3. General multivariate spline theory.

Our articles in this area include [4,5,7,8,9,12,19,20]. As discussed in the last two sections, the notions of **super splines** and **vertex splines**, and the methods of **Neumann series approach** and **noncommutative blending** were introduced in this series of papers. To facilitate the construction schemes, the dimensions of the super spline subspaces should be determined. The first results in this area are given in our paper [12], where a dimension criterion is also introduced. The general theory of super spline, vertex splines, quasi-interpolation, and interpolation in higher dimensions is included in my CBMS-NSF monograph [S3]. In the second edition of my encyclopedia article [S2], cardinal spline interpolation is related to wavelets, a topic to be discussed in Section 5.

4. Applications to engineering problems.

Our results in this area are included in [1,10,11,13,16,18,23,24,25,26]. In addition to construction and implementation of real-time approximation and interpolation schemes, we have found almost immediate applications to image reconstruction [1], design of large reflector surfaces [24], and an application to the boundary element method for electromagnetic scattering [25]. On the other hand, real-time methods should be implemented with the Kalman filter. In our work [10], a parallel algorithm is developed to improve the extended Kalman filter significantly and applications to real-time system parameters identification are given. In the second edition of our monograph [S7], which is under preparation, this method is discussed in some details. When frequency-domain methods are considered, the problem of stability must be considered. By using the Hankel-norm approximation, stability is guaranteed. In our work [11,13,16], computational efficiency and accuracy are discussed relative to truncation of the Hankel operator and the estimates are given in terms of s -numbers (or singular values). A related application is the solution of the so-called four-block problem in systems theory. This is studied in [18]. Robust stability are studied in [23] for the one-variable (i.e. SISO) setting, and in [26] for the multi-variable (i.e. MISO) setting.

5. Wavelets.

Perhaps the most exciting development in this project is the introduction of cardinal-spline wavelets in our work [21,22]. This was done toward the end of the extended period of this project which overlaps with the new project (under Contract No. DAAL 03-90-0091). This new project, with the same title, should be considered as continuation of the old one for which this report is prepared. The multiresolution analysis introduced by Meyer [S22] and Mallat [S19, S20, S21] is followed. As is well-known, Daubechies' wavelets [S16, S17] are the only available compactly supported orthonormal wavelets. However, although there are efficient algorithms (cf. [S17]), these wavelets do not have explicit formulations and are certainly not suitable for real-time applications. In addition, since they are not symmetric or anti-symmetric, their non-linear phase property creates distortion. In [21], we introduced the notion of cardinal-spline wavelets. These wavelets are constructed by using cardinal fundamental splines of Schoenberg. Since they are explicitly formulated, symmetric for even-order splines, and antisymmetric for odd-order splines, they are readily

available for interpolation and wavelet decomposition of data in real-time. An application to curve-design is given in [27], and a comprehensive paper on application to real-time signal analysis is under preparation. The general theory of our new wavelets is studied in [S14], partially supported by the new project. This theory includes both the Daubechies wavelets and our cardinal-spline wavelets as special cases. A fairly complete analysis of the minimally supported cardinal spline wavelets (introduced in [22]) is given in [S15]. A survey article [S3] has been written and will be published by Academic Press, and a tutorial article [S4] which is a compilation of the five-hour lecture series I gave in Lancaster, England, last July, will be published by the Oxford University Press.

References

The list of manuscripts in Section 1 is also used as references. In addition, the following supplementary list is relevant to this report.

- S1. C. de Boor and K. Höllig, Approximation power of smooth bivariate pp functions, *Math. Z.* **197** (1988), 343-363.
- S2. C. K. Chui, Approximation and expansions, *Ency. of Physical Sciences and Technology*, Academic Press, N.Y., 661-687; Second edition (to appear in 1990 or 1991).
- S3. C. K. Chui, *Multivariate Splines*, CBMS-NSF Series in Applied Mathematics # 54, SIAM, Philadelphia, 1988, 189 pp. + vi.
- S4. C. K. Chui, Wavelets and spline interpolation, in *SERC Summer School Proceedings*, W. Light (ed.), Oxford University Press, Lancaster, 1991. To appear.
- S5. C. K. Chui, An overview of wavelets, in *Approximation Theory and Functional Analysis*, C. K. Chui (ed.), Academic Press, New York, 1990. To appear.
- S6. C. K. Chui and G. Chen, *Kalman Filtering with Real-Time Applications*, Springer Series in Information Sciences # 17, Springer-Verlag, 1987.
- S7. C. K. Chui and G. Chen, *Linear Systems and Optimal Control*, Springer Series in Information Sciences # 18, Springer-Verlag, 1988.
- S8. C. K. Chui and G. Chen, *Selected Topics in Signal Processing and Systems Theory*. To appear.
- S9. C. K. Chui and M. J. Lai, On bivariate vertex splines, in *Multivariate Approx. Theory III*, Ed. by W. Schempp and K. Zeller, ISNM 75, Birkhäuser, 1985, 84-115.
- S10. C. K. Chui, W. Schempp and K. Zeller, Editors, *Multivariate Approximation Theory IV*, Birkhäuser, Basel, 1989, 342 pp. + ix.
- S11. C. K. Chui, L.L. Schumaker and F. Utreras, Editors, *Topics in Multivariate Approximation*, Academic Press, N.Y., 1987, 335 pp. + x.
- S12. C. K. Chui, L.L. Schumaker and J.D. Ward, Editors, *Approximation Theory VI: Volume I*, Academic Press, N.Y., 1989, 1-340 + xxv.
- S13. C. K. Chui, L.L. Schumaker and J.D. Ward, Editors, *Approximation Theory VI: Volume II*, Academic Press, N.Y., 1989, 341-692 + xxiv.
- S14. C. K. Chui and J. Z. Wang, A general framework of compactly supported splines and wavelets, CAT Report #219, Texas A&M University.
- S15. C. K. Chui and J. Z. Wang, An analysis of cardinal-spline wavelets, under preparation.

- S16. I. Daubechies, Orthogonal bases of compactly supported wavelets, *Comm. Pure and Appl. Math.* **41** (1988), 909-996.
- S17. I. Daubechies, *Wavelets*, CBMS-NSF Series in Applied Math., SIAM Publ., Philadelphia, to appear.
- S18. T. Lyche and L. L. Schumaker, *Mathematical Methods in Computer Aided Geometric Design*, Academic Press, N. Y., 1989.
- S19. S. Mallat, *Multiresolution representation and wavelets*, Ph.D. Thesis, Univ. of Penn., Philadelphia, 1988.
- S20. S. Mallat, Theory for multiresolution signal decomposition: the wavelet representation, *IEEE Trans. on Pattern Analysis and Machine Intelligence* **2** (1989), 674-693.
- S21. S. Mallat, Multifrequency channel decompositions of images and wavelet models. *IEEE Trans. ASSP* **37** (1989), 2091-2110.
- S22. Y. Meyer, *Ondelettes et Opérateurs* (Two volumes), Hermann Publ., Paris, 1990.

IV. Bibliography

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B.S. (Applied Mathematics, Electrical Engineering, Physics)
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III. ACADEMIC CAREER:

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1987–1989	Professor of Mathematics and of Electrical Engineering Texas A&M University
1984–1986	Head, Division of Applied Mathematics Texas A&M University
1974–1987	Professor of Mathematics Texas A&M University
1970–1974	Associate Professor of Mathematics Texas A&M University
1967–1970	Assistant Professor of Mathematics State University of New York at Buffalo Amherst, New York
1967	Post Doctoral Research Associate University of California at San Diego La Jolla, California
Visiting Positions: Florence, Italy; Canterbury, New Zealand; Cambridge, England	

IV. JOURNAL EDITORSHIPS:

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- (2) Editor of Journal of Approximation Theory
- (3) Associate Editor of Journal of Mathematical Research and Exposition
- (4) Associate Editor of Revista de Matemáticas Aplicadas

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Distinguished Achievement Award in Research
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May 7, 1981

VI. HONORS:

- (1) National Science Foundation CBMS Principal Speaker, 1987
- (2) Honorary Professor, Ningxia University, China, 1987
- (3) Guest Chair Professor, Xiamen University, China, 1987
- (4) Erskine Fellow, University of Canterbury, New Zealand, 1987
- (5) NATO Advanced Study Institute Principal Speaker, 1989
- (6) Principal Speaker, Spline Symposium at Tokyo, Japan, 1990

VII. PROFESSIONAL SOCIETIES:

- (1) American Mathematical Society
- (2) Mathematical Association of America
- (3) Society for Industrial and Applied Mathematics
- (4) Institute of Electrical and Electronics Engineers

VIII. RESEARCH AREAS:

- (1) Approximation Theory
(multivariate splines, wavelets)
- (2) Applied Mathematics
(real-time algorithms, systems theory, signal processing,
boundary element methods, nonlinear optics)

PUBLICATIONS

A. Books:

1. *Approximation Theory II*, (with G.G. Lorentz and L.L. Schumaker, Editors), Academic Press, N.Y., 1976. 558 pp + xi.
2. *Elements of Calculus*, (with D. Allen and W. Perry), Brooks-Cole, Monterey, Calif., 1983; and Second Edition, 1988.
3. *Approximation Theory IV*, (with L.L. Schumaker and J.D. Ward, Editors), Aca-

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4. *Approximation Theory V*, (with L.L. Schumaker and J.D. Ward, Editors), Academic Press, N.Y., 1986, 654 pp. + xviii.
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 7. *Topics in Multivariate Approximation*, (with L.L. Schumaker and F. Utreras, Editors), Academic Press, N.Y., 1987, 335 pp. + x.
 8. *Multivariate Splines*, CBMS-NSF Series in Applied Mathematics # 54, SIAM, Philadelphia, 1988, 189 pp. + vi. (Translation into Japanese.)
 9. *Approximation Theory VI: Volume I*, (with L.L. Schumaker and J.D. Ward, Editors), Academic Press, N.Y., 1989, 1-340 + xxv.
 10. *Approximation Theory VI: Volume II*, (with L.L. Schumaker and J.D. Ward, Editors), Academic Press, N.Y., 1989, 341-692 + xxiv.
 11. *Multivariate Approximation Theory IV*, (with W. Schempp and K. Zeller, Editors), Birkhäuser, Basel, 1989, 342 pp. + ix.
 12. *Approximation Theory and Functional Analysis*, Academic Press, N.Y., 1990. To appear.
 13. *Selected Topics in Signal Processing and Systems Theory* (with G. Chen). To appear.
 14. *Wavelets with Emphasis on Time-Frequency Analysis*. To appear.

B. Research Papers:

1. Bounded approximation by polynomials with restricted zeros, Bull. Amer. Math. Soc., Vol. 73 (1967), 967-972.
2. Bounded approximation by polynomials whose zeros lie on a circle, Trans. Amer. Math. Soc., Vol. 138 (1968), 171-182.
3. A convergence theorem for certain Riemann sums, Can. Math. Bull., Vol. 12 (1969), 523-525.
4. Potentials of families of unit masses on disjoint Jordan curves, (with J. Korevaar), in *Abstract Spaces and Approximation*, Ed. by P.L. Butzer and B. Sz-Nagy, ISBM, Vol. 10 (1969), Basel, pp. 338-350.
5. On measures of n-fold symmetry of convex sets, (with M.N. Parnes), Proc. Amer. Math. Soc., Vol. 26 (1970), 480-486.
6. C-polynomial approximation of H^p and $\mathcal{H}^p$ functions, J. Math. Anal. Appl., Vol. 34 (1971), 82-85.
7. A lower bound of fields due to unit point masses, Amer. Math. Monthly, Vol. 78 (1971), 779-780.
8. Approximation by overconvergence of a power series, (with M.N. Parnes), J. Math. Anal. Appl., Vol. 36 (1971), 693-696.

9. Concerning rates of convergence of Riemann sums, *J. Approximation Theory*, Vol. 4 (1971), 279–287.
10. Polynomial approximation on a polydisc, *J. Australian Math. Soc.*, Vol. 14 (1972), 216–218.
11. Concerning Gaussian-Chebyshev quadrature errors, *SIAM J. Numerical Analysis*, Vol. 9 (1972), 237–240.
12. Representation of a function in terms of its mean boundary values, (with C.H. Ching), *Bull. Aust. Math. Soc.*, Vol. 7 (1972), 425–427.
13. Uniqueness and nonuniqueness of mean boundary value problems, (with C.H. Ching), *Bull. Aust. Math. Soc.*, Vol. 8 (1973) 23–26.
14. Polynomial approximation and distribution of electrons. *J. Approximation Theory*. Vol. 7 (1973), 355–365.
15. Some trigonometric inequalities in approximation theory, (with C.H. Ching), *Bull. Aust. Math. Soc.*, Vol. 8 (1973), 393–397.
16. A representation formula for harmonic functions, (with C.H. Ching), *Proc. Amer. Math. Soc.*, Vol. 39 (1973), 349–352.
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19. Convergence of certain quadrature processes, *Aeq. Math.*, Vol. 9 (1973), 242–244.
20. Approximation of functions from their means, (with C.H. Ching), in *Approximation Theory*, Ed. by G.G. Lorentz, Academic Press 1973, pp. 307–313.
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23. Asymptotic similarities of Fourier and Riemann coefficients, (with C.H. Ching), *J. Approximation Theory*, Vol. 10 (1974), 295–300.
24. Mean boundary value problems and Riemann series, (with C.H. Ching), *J. Approximation Theory*, Vol. 10 (1974), 324–336.
25. Delange's characterization of the sine function, (with C.H. Ching), *Glasgow Math. Journal*, Vol. 15 (1974), 66–68.
26. Limit set of power series outside the circles of convergence, (with M.N. Parnes), *Pacific J. Math.*, Vol. 50 (1974), 403–423.
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