

```

[2][10] INT16 data:
INT capt.no, work.no:
SEQ
  capt.no := 0
  work.no := 1
  ... Acquire data and store in data[1, 0 FOR 10]
SEQ
  PAR
    ... Acquire data and store in data[capt.no, 0 FOR 10]
    ... Scheduling process with data[work.no, 0 FOR 10]
  capt.no := work.no
  work.no := 1-capt.no

```

(P-12)

## Correspondence

### SOLVING SINGULAR SYSTEMS USING ORTHOGONAL FUNCTIONS

*Indexing terms:* Matrix algebra, Mathematical techniques, Control systems, Control theory

**Abstract:** Orthogonal functions, and, in particular, Walsh functions, have been advocated in the literature as a method of approximating the solutions of singular systems  $Ex' = Fx + Bu$  of index  $k$ . This paper gives the first analysis of the accuracy of these approximations. For Walsh functions, divergence is shown for  $k \geq 3$  and convergence for  $k = 0, 1$ . The  $k = 2$  case is also analysed.

#### 1 Introduction

The singular control system

$$Ex'(t) = Fx(t) + Bu(t), x(t_0) = x_0 \quad (1)$$

with  $E, F, B$  constant matrices and  $E$  singular, has been extensively studied [3, 4, 8]. In Reference 11 it was suggested that eqn. 1 could be solved using orthogonal functions. This was discussed further in References 5, 9 and 10. Walsh functions were used because of their simple structure and the ease of approximating coefficients. While these papers showed that one could solve the resulting algebraic equations for the coefficients of an approximation, none of them actually examined how good these approximations were. In this paper, we give the first discussion of the convergence of the Walsh approximations for singular systems. It will be shown that, in many cases, the approximations actually diverge from the true solutions, as more terms are used in the approximation.

#### 2 Orthogonal approximations

Suppose that  $E$  and  $F$  are  $n \times n$  matrices and eqn. 1 is solvable. That is,  $\lambda E + F$  is a regular pencil, so that  $\det(\lambda E + F) \neq 0$  and eqn. 1 has a solution for every sufficiently smooth  $u$  and consistent  $x_0$  [3]. We consider real  $E, F, B, x$  and  $u$ , but the complex case is similar. The time interval is taken to be  $[0, 1]$ .

First, we review the suggested solution of eqn. 1 by orthogonal functions. Let  $\mathcal{L}^2$  be the space of all square integrable Lebesgue measurable functions on  $[0, 1]$ .  $\mathcal{L}^2$  is a Hilbert space, with inner product

$$\langle f, g \rangle = \int_0^1 f(t)g(t) dt$$

and associated norm

$$\|f\| = \left( \int_0^1 |f(t)|^2 dt \right)^{1/2} \quad (2)$$

A vector-valued function will be said to be in  $\mathcal{L}^2$ , if each co-ordinate is in  $\mathcal{L}^2$ . Let  $\{\psi_i(t)\}_{i=1}^\infty$  be an orthonormal basis for  $\mathcal{L}^2$ . Then, if  $f \in \mathcal{L}^2$ , we have

$$f(t) = \sum_{i=1}^\infty f_i \psi_i(t) \quad (3)$$

where the  $f_i$  are the Fourier coefficients of  $f$  with respect to the basis  $\{\psi_i\}$ . The series of eqn. 3 converges in the norm of eqn. 2. For a given orthonormal basis  $\{\psi_i\}$ , let  $\Psi_m = [\psi_1, \dots, \psi_m]^T$ , and define the projection onto the span of  $\{\psi_1, \dots, \psi_m\}$  by

$$\mathcal{P}_m(f) = \sum_{i=1}^m f_i \psi_i$$

The coefficients of this projection are given by the operator

$$\mathcal{W}_m(f) = [f_1, \dots, f_m]$$

For a vector  $a = [a_1, \dots, a_m]$ , define

$$\mathcal{P}_m(a) = \sum_{i=1}^m a_i \psi_i$$

If  $f$  is vector valued, then  $\mathcal{W}_m(f)$  is a matrix with  $ij$ th entry is the  $j$ th Fourier coefficient of the  $i$ th element of  $f$ . Similarly, the  $a_i$  in the definition of  $\mathcal{P}_m$  can be vectors. Note that  $\mathcal{P}_m(f) = \mathcal{W}_m(f)\Psi_m$ . Finally, define the  $m \times m$  matrix  $P_m$  by

$$\mathcal{W}_m \left( \int_0^1 \Psi_m(s) ds \right) = P_m$$

To 'solve' the singular system of eqn. 1, fix  $m$  and take  $X = \mathcal{W}_m(x)$ ,  $U = \mathcal{W}_m(u)$ ,  $Q = \mathcal{W}_m(x_0)$  where  $x_0$  is considered to be a constant function. Integrating eqn. 1 gives

$$Ex(t) - Ex_0 = F \int_0^t x(s) ds + B \int_0^t u(s) ds \quad (4)$$

# Solving Singular Systems

**Kristine K. Fowler**



## **Solving Singular Systems:**

Methods of Solving Singular Systems of Ordinary Differential Equations I. U. Eremeevich Boiakov, 1992 This text is a response to the author's previous monograph Regular and Singular Systems of Linear Ordinary Differential Equations. He has applied the results presented in that book to construct stable difference and other approximations to singular systems of ordinary differential equations. He also gives an account of the present state of the problem and a review of the latest publications.

**Krylov Methods for Nonsymmetric Linear Systems** Gérard Meurant, Jurjen Duintjer Tebbens, 2020-10-02 This book aims to give an encyclopedic overview of the state of the art of Krylov subspace iterative methods for solving nonsymmetric systems of algebraic linear equations and to study their mathematical properties. Solving systems of algebraic linear equations is among the most frequent problems in scientific computing; it is used in many disciplines such as physics, engineering, chemistry, biology, and several others. Krylov methods have progressively emerged as the iterative methods with the highest efficiency while being very robust for solving large linear systems; they may be expected to remain so independent of progress in modern computer-related fields such as parallel and high performance computing. The mathematical properties of the methods are described and analyzed along with their behavior in finite precision arithmetic. A number of numerical examples demonstrate the properties and the behavior of the described methods. Also considered are the methods' implementations and coding as Matlab-like functions. Methods which became popular recently are considered in the general framework of Q-OR (quasi-orthogonal) Q-MR (quasi-minimum residual) methods. This book can be useful for both practitioners and for readers who are more interested in theory. Together with a review of the state of the art, it presents a number of recent theoretical results of the authors, some of them unpublished, as well as a few original algorithms. Some of the derived formulas might be useful for the design of possible new methods or for future analysis. For the more applied user, the book gives an up-to-date overview of the majority of the available Krylov methods for nonsymmetric linear systems, including well-known convergence properties and, as we said above, template codes that can serve as the base for more individualized and elaborate implementations.

Generalized Inverses: Theory and Computations Guorong Wang, Yimin Wei, Sanzheng Qiao, 2018-05-12 This book begins with the fundamentals of the generalized inverses, then moves to more advanced topics. It presents a theoretical study of the generalization of Cramer's rule, determinant representations of the generalized inverses, reverse order law of the generalized inverses of a matrix product, structures of the generalized inverses of structured matrices, parallel computation of the generalized inverses, perturbation analysis of the generalized inverses, an algorithmic study of the computational methods for the full rank factorization of a generalized inverse, generalized singular value decomposition, imbedding method, finite method, generalized inverses of polynomial matrices, and generalized inverses of linear operators. This book is intended for researchers, postdocs, and graduate students in the area of the generalized inverses with an undergraduate level understanding of linear algebra.

Solving Singular

Systems Using Orthogonal Functions Stephen L. Campbell, Kevin D. Yeomans, NORTH CAROLINA STATE UNIV AT RALEIGH CENTER FOR RESEARCH IN SCIENTIFIC COMPUTATION., 1987 Orthogonal functions and in particular Walsh functions have been advocated in the literature as a method of approximating the solutions of singular systems  $Ex = Fx + Bu$  of index  $k$  This paper gives the first analysis of the accuracy of these approximations For Walsh functions divergence is shown for  $k \geq 3$  and convergence for  $k \leq 1$  The index two case is also analyzed Keywords Singular control systems Constant matrices Coefficients

Guide to Scientific Computing in C++ Joe Pitt-Francis, Jonathan Whiteley, 2012-02-18 This easy to read textbook reference presents an essential guide to object oriented C programming for scientific computing With a practical focus on learning by example the theory is supported by numerous exercises Features provides a specific focus on the application of C to scientific computing including parallel computing using MPI stresses the importance of a clear programming style to minimize the introduction of errors into code presents a practical introduction to procedural programming in C covering variables flow of control input and output pointers functions and reference variables exhibits the efficacy of classes highlighting the main features of object orientation examines more advanced C features such as templates and exceptions supplies useful tips and examples throughout the text together with chapter ending exercises and code available to download from Springer

**Introduction to Numerical Ordinary and Partial Differential Equations Using MATLAB** Alexander Stanoyevitch, 2011-10-14 **Continuous Time Dynamical Systems** B.M. Mohan, S.K. Kar, 2018-10-08 Optimal control deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved An optimal control is a set of differential equations describing the paths of the control variables that minimize the cost functional This book Continuous Time Dynamical Systems State Estimation and Optimal Control with Orthogonal Functions considers different classes of systems with quadratic performance criteria It then attempts to find the optimal control law for each class of systems using orthogonal functions that can optimize the given performance criteria Illustrated throughout with detailed examples the book covers topics including Block pulse functions and shifted Legendre polynomials State estimation of linear time invariant systems Linear optimal control systems incorporating observers Optimal control of systems described by integro differential equations Linear quadratic Gaussian control Optimal control of singular systems Optimal control of time delay systems with and without reverse time terms Optimal control of second order nonlinear systems Hierarchical control of linear time invariant and time varying systems *Applied Optimization* Ross Baldick, 2006-05-04 Step by step descriptions of how to formulate numerical problems to be solved by existing software *Scientific and Technical Aerospace Reports*, 1990

**Analysis of Numerical Methods** Eugene Isaacson, Herbert Bishop Keller, 2012-04-26 This excellent text for advanced undergraduate and graduate students covers norms numerical solutions of linear systems and matrix factoring eigenvalues and eigenvectors polynomial approximation and more Many examples and problems 1966 edition **Proceedings of the Cornelius Lanczos International Centenary Conference** J. David Brown, 1994-01-01 *Sensor Imaging Systems for*

*Real-Time Applications* S. Kannadhasan, R. Nagarajan, T. Kamalakannan, M. Chandrasekaran, N.

Shanmugasundaram, 2025-09-12 Recent sensor technologies have spurred innovation across many industries and have been employed worldwide to improve transportation medical treatment nanotechnology mobile devices virtual and augmented reality and artificial intelligence This new volume looks at different aspects and kinds of sensors such as wearable radio frequency devices machine learning algorithms for sensors intelligent monitoring systems using RFID technologies UV based control systems Booth algorithm based sensors for improved multipliers sensor data analysis using Arduino piezoelectric sensor signaling and more Myriad examples of novel applications of sensor technology are presented in different areas such as In disaster management such as for accident detection and rescue systems For development of smart healthcare technology such as for early prediction of breast cancer monitoring and gauging of polluted air to alert for asthma triggers In transportation such as in the development of smart helmets for protective driving for vehicle to vehicle communication for accident prevention for enabling vehicles to sense rough terrain In urban engineering smart city management such as for locating underground cable faults for sewage surveillance for blockages and hazardous gases and chemical contaminants In agriculture such as using sensors for agricultural pest control using IoT for automated drip irrigation For residential and office use such as for energy management systems for monitoring ergonomic behaviors Other chapters present sensor technology for audio and voice impaired individuals for smart shopping using smart trolley and more Offering a plethora of examples of how sensor imaging can be applied for real time solutions this volume will provide inspiration for industry professionals and faculty and students in electronics and communication engineering interested in finding solutions to today's problems using sensor technology

**Control, Computation and Information Systems** P. Balasubramaniam, 2011-02-04

This book constitutes the refereed proceedings of the International Conference on Logic Information Control and Computation ICLICC 2011 held in Gandhigram India in February 2011 The 52 revised full papers presented were carefully reviewed and selected from 278 submissions The papers are organized in topical sections on control theory and its real time applications computational mathematics and its application to various fields and information sciences focusing on image processing and neural networks

Compstat Rudolf Dutter, Wilfried Grossmann, 2013-12-20 This book assembles papers which were presented at the biennial symposium in Computational Statistics held under the auspices of the International Association for Statistical Computing IASC a section of ISI the International Statistical Institute This symposium named COMPSTAT 94 was organized by the Statistical Institutes of the University of Vienna and the University of Technology of Vienna Austria The series of COMPSTAT Symposia started 1974 in Vienna Meanwhile they took place every other year in Berlin Germany 1976 Leiden The Netherlands 1978 Edinburgh Great Britain 1980 Toulouse France 1982 Prague Czechoslovakia 1984 Rome Italy 1986 Copenhagen Denmark 1988 Dubrovnik Yugoslavia 1990 and Neuchâtel Switzerland 1992 This year we are celebrating the 20th anniversary in Vienna Austria It has obviously been observed a movement from

traditional computational statistics with emphasis on methods which produce results quickly and reliably to computationally intensive methods like resampling procedures Bayesian methods dynamic graphics to very recent areas like neural networks accentuation on spatial statistics huge data sets analysis strategies etc For the organization of the symposium new guidelines worked out by the IASC in written form were in effect this time The goal was to refresh somehow the spirit of the start of COMPSTAT 74 keep the tradition of the series and ensure a certain continuity in the sequence of biannual meetings

**Matrix Analysis and Applied Linear Algebra** Carl D. Meyer, 2000-06-01 This book avoids the traditional definition theorem proof format instead a fresh approach introduces a variety of problems and examples all in a clear and informal style The in depth focus on applications separates this book from others and helps students to see how linear algebra can be applied to real life situations Some of the more contemporary topics of applied linear algebra are included here which are not normally found in undergraduate textbooks Theoretical developments are always accompanied with detailed examples and each section ends with a number of exercises from which students can gain further insight Moreover the inclusion of historical information provides personal insights into the mathematicians who developed this subject The textbook contains numerous examples and exercises historical notes and comments on numerical performance and the possible pitfalls of algorithms Solutions to all of the exercises are provided as well as a CD ROM containing a searchable copy of the textbook

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required in the mathematical library and helps mathematicians find resources in any format in the mathematics literature It lists a wide range of standard texts journals review articles newsgroups and Internet and database tools for every major subfield in mathematics and details methods of access to primary literature sources of new research applications results and techniques Using the Mathematics Literature is the most comprehensive and up to date resource on mathematics literature in both print and electronic formats presenting time saving strategies for retrieval of the latest information **Applied**

**Parallel and Scientific Computing** Pekka Manninen, Per Öster, 2013-02-12 This volume constitutes the refereed proceedings of the 11th International Conference on Applied Parallel and Scientific Computing PARA 2012 held in Helsinki Finland in June 2012 The 35 revised full papers presented were selected from numerous submissions and are organized in five technical sessions covering the topics of advances in HPC applications parallel algorithms performance analyses and optimization application of parallel computing in industry and engineering and HPC interval methods In addition three of the topical minisymposia are described by a corresponding overview article on the minisymposia topic In order to cover the state of the art of the field at the end of the book a set of abstracts describe some of the conference talks not elaborated into full articles

**Sliding Mode Control of Uncertain Parameter-Switching Hybrid Systems** Ligang Wu, Peng Shi, Xiaojie Su, 2014-05-27 In control theory sliding mode control SMC is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to slide along a cross section of the system's normal behaviour In recent years SMC has been successfully applied to a wide variety of practical engineering systems including robot manipulators aircraft underwater vehicles spacecraft flexible space structures electrical motors power systems and automotive engines Sliding Mode Control of Uncertain Parameter Switching Hybrid Systems addresses the increasing demand for developing SMC technologies and comprehensively presents the new state of the art sliding mode control methodologies for uncertain parameter switching hybrid systems It establishes a unified framework for SMC of Markovian jump singular systems and proposes new SMC methodologies based on the analysis results A series of problems are solved with new approaches for analysis and synthesis of switched hybrid systems including stability analysis and stabilization dynamic output feedback control and SMC A set of newly developed techniques e.g. average dwell time piecewise Lyapunov function parameter dependent Lyapunov function cone complementary linearization are exploited to handle the emerging mathematical computational challenges Key features Covers new concepts new models and new methodologies with theoretical significance in system analysis and control synthesis Includes recent advances in Markovian jump systems switched hybrid systems singular systems stochastic systems and time delay systems Includes solved problems Introduces advanced techniques Sliding Mode Control of Uncertain Parameter Switching Hybrid Systems is a comprehensive reference for researchers and practitioners working in control engineering system sciences and applied mathematics and is also a useful source of information for senior undergraduate and graduates studying in these areas

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