The Constrained Conjugate Gradient Algorithm

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Abstract—Based on the condition for equivalence between linearly constrained minimum-variance (LCMV) filters and their generalized sidelobe canceler (GSC) implementations, we derive the new constrained conjugate gradient (CCG) algorithm. We discuss the use of orthogonal and nonorthogonal blocking matrices for the GSC structure and how the choice of this matrix may affect the relationship with the LCMV counterpart. The newly derived algorithm was tested in a computer experiment for adaptive multiuser detection and showed excellent results.

Index Terms—Conjugate gradient algorithm, constrained adaptive filtering.

I. INTRODUCTION

LINEARLY constrained adaptive filters have been used in many applications including adaptive beamforming with sensor arrays and blind adaptive interference cancellation in multiuser mobile communication systems. The constrained version of the least mean square (LMS) algorithm (CLMS) was proposed in [1] for the minimization of the output-error energy of a finite impulse response (FIR) filter subject to a set of known linear constraints, i.e., $\min_{\mathbf{w}} E[e^2]$ subject to $\mathbf{C}^T \mathbf{w} = \mathbf{f}$, where $\mathbf{w}$ is the length M coefficient vector, e is the filter output error, $\mathbf{C}$ is the $M \times p$ constraint matrix, and $\mathbf{f}$ is the length p gain vector. In [2], an alternative structure was presented whereby only a smaller set of coefficients are updated, which are confined to the subspace orthogonal to the space spanned by the constraint matrix $\mathbf{C}$. This structure, known as the generalized sidelobe canceler (GSC), is able to transform the linearly constrained minimization problem into an unconstrained minimization problem, and therefore can accommodate virtually any adaptation algorithm. Although the constrained algorithm and its GSC implementation are assumed to present identical steady-state performance [2] in a stationary environment, different choices of the blocking matrix $\mathbf{B}$ such that $\mathbf{B}^T \mathbf{C} = \mathbf{0}$ leads to different results. Moreover, this matrix determines the computational complexity of the adaptation algorithm implemented in the GSC structure. This paper revisits the condition of equivalence between a constrained adaptive filter and its GSC counterpart and uses this condition to introduce a new constrained algorithm, the constrained conjugate gradient (CCG) algorithm.

II. PRELIMINARIES

The CLMS solution to the linearly constrained minimum-variance (LCMV) problem is given by [1]

$$\mathbf{w}(k+1) = \mathbf{P}\mathbf{w}(k) - \mu y(k)\mathbf{P}\mathbf{x}(k) + \mathbf{F} \tag{1}$$

where

$$\mathbf{F} = \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{f};$$
$$\mathbf{P} = \mathbf{I} - \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T \quad \text{projection matrix onto the subspace orthogonal to the subspace spanned by the constraint matrix,}$$

and the output signal:

$$y(k) = \mathbf{w}^T(k)\mathbf{x}(k), \text{ output signal.}$$

$\mathbf{x}(k)$ is the input-signal vector containing present and past input-signal samples $[x(k) \, x(k-1) \, \cdots \, x(k-M+1)]^T$. We recall the fact that although $\mathbf{P}\mathbf{w}(k) + \mathbf{F}$ corresponds to $\mathbf{w}(k)$ in infinite precision, the computation as in (1) is necessary in a limited-precision-arithmetic machine in order to avoid any drift from the constraint plane [1].

The GSC decomposes the coefficient vector by using a transformation matrix given by $\mathbf{T} = [\mathbf{C} \vdots \mathbf{B}]$ where $\mathbf{B}$ is called blocking matrix, and it spans the null space of the constraint matrix $\mathbf{C}$. The GSC-transformed coefficient vector in $\mathbf{w}(k) = \mathbf{T}\mathbf{w}(k)$ is partitioned as $\bar{\mathbf{w}}(k) = [\mathbf{w}_U^T \vdots -\mathbf{w}_L^T]^T$, where the upper part is constant and chosen such that $\mathbf{C}\mathbf{w}_U$ corresponds to $\mathbf{F} = \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{f}$, and $-\mathbf{w}_L = \mathbf{w}_{GSC}(k)$ is updated according to an unconstrained adaptive filter such that the overall coefficient vector corresponds to $\mathbf{w}(k) = \mathbf{F} - \mathbf{B}\mathbf{w}_{GSC}(k)$.

The inverse of the GSC transformation matrix (guaranteed by linearly independent columns of $\mathbf{B}$ and $\mathbf{C}$, and by $\mathbf{B}^T\mathbf{C} = \mathbf{0}$ [3]) can be partitioned as $\mathbf{T}^{-1} = [\mathbf{A}_1^T \vdots \mathbf{A}_2^T]^T$ where $\mathbf{A}_1 = (\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T$ and $\mathbf{A}_2 = (\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T$.

By replacing $\mathbf{A}_1$ and $\mathbf{A}_2$ in $\mathbf{T}^{-1}$ and then in $\mathbf{T}\mathbf{T}^{-1} = \mathbf{I}$ we find another expression for the projection matrix $\mathbf{P}$, as obtained in [4]

$$\mathbf{P} = \mathbf{B}(\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T. \tag{2}$$

III. EQUIVALENCE CONDITION REVISITED

In this section, we obtain the CLMS algorithm from its GSC implementation in order to find under which circumstances they are equivalent in infinite precision. The GSC coefficient-vector update equation using the LMS algorithm relates to the coefficient-vector update equation for the constrained LMS algorithm according to

$$\mathbf{w}(k+1) = \mathbf{F} - \mathbf{B}[\mathbf{w}_{GSC}(k+1)]$$
$$= \mathbf{F} - \mathbf{B}[\mathbf{w}_{GSC}(k) + \mu e_{GSC}(k)\mathbf{x}_{GSC}(k)] \tag{3}$$

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A Conjugate Gradient Algorithm for Analysis of Variance Computations Byung Chun Kim,1984   Fitting Linear Models A. McIntosh,2012-12-06 The increasing power and decreasing price of smalI computers especialIy personal computers has made them increasingly popular in statistical analysis The day may not be too far off when every statistician has on his or her desktop computing power on a par with the large mainframe computers of 15 or 20 years ago These same factors make it relatively easy to acquire and manipulate large quantities of data and statisticians can expect a corresponding increase in the size of the datasets that they must analyze Unfortunately because of constraints imposed by architecture size or price these smalI computers do not possess the main memory of their large cousins Thus there is a growing need for algorithms that are sufficiently economical of space to permit statistical analysis on smalI computers One area of analysis where there is a need for algorithms that are economical of space is in the fitting of linear models   **Non-orthogonal Analysis of Variance Using a Generalized Conjugate Gradient Algorithm** Stanford University. Computer Science Department. Numerical Analysis Project,G. H. Golub,S. G. Nash,1980   *An Algorithm for Unbalanced Multifactorial ANOVA Models with Contrasts* Hongsuk Jorn,1986   **Collected Algorithms from ACM.** ,1989 A collation of all algorithms including certifications and remarks that have appeared in the Algorithms Department of Communications of the ACM since 1960   *Proceedings of the Statistical Computing Section* American Statistical Association. Statistical Computing Section,1983   *Soft Computing Techniques in Solid Waste and Wastewater Management* Rama Rao Karri,R Gobinath,Mohammad Hadi Dehghani,2021-07-24 Soft Computing Techniques in Solid Waste and Wastewater Management is a thorough guide to computational solutions for researchers working in solid waste and wastewater management operations This book covers in depth analysis of process variables their effects on overall efficiencies and optimal conditions and procedures to improve performance using soft computing techniques These topics coupled with the systematic analyses described will help readers understand various techniques that can be effectively used to achieve the highest performance In depth case studies along with discussions on applications of various soft computing techniques help readers control waste processes and come up with short term mid term and long term strategies Waste management is an increasingly important field due to rapidly increasing levels of waste production around the world Numerous potential solutions for reducing waste production are underway including applications of machine learning and computational studies on waste management processes This book details the diverse approaches and techniques in these fields providing a single source of information researchers and industry practitioners It is ideal for academics researchers and engineers in waste management environmental science environmental engineering and computing with relation to environmental science and waste management Provides a comprehensive reference on the implementation of soft computing techniques in waste management drawing together current research and future implications Includes detailed algorithms used enabling authors to understand

and appreciate potential applications Presents relevant case studies in solid and wastewater management that show real world applications of discussed technologies   **Proceedings of the International Conference on Geomechanics and Numerical Simulation (ICGNS 2025)** Yuan Wang,Huaining Ruan,2026-02-09 This book gathers the latest research and practical innovations that tackle critical issues in geotechnical design hazard mitigation and intelligent simulation Advances in geomechanics and computational methods are transforming how engineers and researchers address infrastructure safety and resilience By linking theoretical progress with engineering practice it delivers actionable insights for improving system reliability and reducing risks to communities The book explores three major themes The first focuses on geomechanics and constitutive modeling analyzing the behavior of geomaterials under varied environmental and loading conditions Both established approaches such as elastoplasticity and critical state soil mechanics and advanced multi field coupling models are presented with attention to experimental validation and parameter calibration for accurate modeling The second theme addresses geotechnical engineering and hazard mitigation Topics include foundation stability slope reinforcement tunneling mechanics and retaining wall design supported by real world case studies Special focus is given to geohazard risk assessment of earthquakes landslides and subsidence The integration of monitoring tools remote sensing and IoT based sensing systems is highlighted as a path toward proactive early warning and disaster management The third theme highlights numerical simulation and intelligent computing in geomechanics Finite and discrete element methods are discussed alongside deep learning Bayesian optimization high performance computing and digital twins These techniques enable real time decision support enhance efficiency and open new opportunities for adaptive and intelligent geotechnical analysis This book stands out by uniting geomechanics modeling simulation and intelligent technologies in one resource It serves as a valuable reference for researchers engineers and practitioners in civil and geotechnical engineering as well as computational modeling Graduate students and professionals aiming to deepen their expertise in geomechanics and disaster resilience will also benefit The content supports academic study and engineering practice bridging theory and application to address urgent challenges in infrastructure development and geohazard prevention   **Realizing Teracomputing** Walter Zwieflhofer,Norbert Kreitz,2003 Geosciences and in particular numerical weather prediction are demanding the highest levels of available computer power The European Centre for Medium Range Weather Forecasts with its experience in using supercomputers in this field organizes every other year a workshop bringing together manufacturers computer scientists researchers and operational users to share their experiences and to learn about the latest developments This book provides an excellent overview of the latest achievements in and plans for the use of new parallel techniques in meteorology climatology and oceanography The proceedings have been selected for coverage in Index to Scientific Technical Proceedings ISTP CDROM version ISI Proceedings   **Journal of the American Statistical Association** ,2006   **Scientific and Technical Aerospace Reports** ,1980 Lists citations with abstracts for aerospace related reports obtained from world wide

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