The Constrained Conjugate Gradient Algorithm

J. A. Apolinário, Jr., *Member, IEEE*, M. L. R. de Campos, *Member, IEEE*, and C. P. Bernal O.

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]

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

where

$\mathbf{F} = \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{f};$

$\mathbf{P} = \mathbf{I} - \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T$ projection matrix onto the subspace orthogonal to the subspace spanned by the constraint matrix, and the output signal:

$y(k) = \mathbf{w}^T(k)\mathbf{x}(k)$, 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 $\mathbf{w}(k) = [\mathbf{w}_U^T\, \vdots\, -\mathbf{w}_L^T]^T$, 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]

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

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

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

A Conjugate Gradient Algorithm For Analysis Of Variance

R Barnett

A Conjugate Gradient Algorithm For Analysis Of Variance:

 A Conjugate Gradient Algorithm for Analysis of Variance Computations Byung Chun Kim,1984   <u>Fitting Linear</u> <u>Models</u> 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

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