

Two-Dimensional Delta-Operator Formulated Discrete-Time Systems: State-Space Realization and Its Coefficient Sensitivity Properties

K. Premaratne, M. M. Ekanayake, J. I. Suarez, and P. H. Baser

Abstract—Delta-operator based implementation of one-dimensional (1-D) discrete-time systems has been the focus of considerable research activity because of its superior finite wordlength properties and possibility of addressing both continuous- and discrete-time systems in a unified manner. In this correspondence, we investigate its corresponding two-dimensional (2-D) implementation by introducing the delta-operator based counterpart to the Roesser local state-space model, the corresponding gramians, and the notion of a balanced realization. The computation of the latter and coefficient sensitivity properties of the resulting implementations are also studied.

Index Terms—Digital filters, finite wordlength effects, fixed-point arithmetic, floating-point arithmetic, multidimensional digital filters, multidimensional systems, sensitivity, state space methods.

I. INTRODUCTION

Conventional implementation of one-dimensional (1-D) discrete-time systems utilize the shift operator (or, q -operator). However, in high-performance applications that may involve high sampling rates and/or shorter wordlengths, these can exhibit unacceptable ill-conditioning problems [1]. Delta-operator (or, δ -operator) based implementations have been proposed as a viable alternative for 1-D systems [1]. They provide superior roundoff noise [1] and coefficient sensitivity [2] properties, and the δ -operator makes it possible to treat both continuous-time (CT) and discrete-time (DT) systems in a unified manner [1]. This correspondence presents a local state-space (s.s.) model for two-dimensional (2-D) δ -operator based implementations; it is the counterpart to the q -operator-based Roesser model [3]. The notions of gramians and balanced (BL) realization are introduced. Computation of the latter is also investigated. A study of the coefficient sensitivity properties of these models reveals that under mild conditions, the proposed Roesser δ -model performs better than the more conventional Roesser q -model.

II. PRELIMINARIES

The notation used is as follows:

$\mathbb{R}, \mathbb{C}, \mathbb{N}$	reals, complex numbers, and nonnegative integers;
$\mathbb{R}^{q \times p}, \mathbb{C}^{q \times p}$	sets of matrices of size $q \times p$ over $\mathbb{R}$ and $\mathbb{C}$;
I_n	unit matrix of size $n \times n$;

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$\{a_{i,j}\}$	elements of matrix A ;
A^*, A^T	complex conjugate transpose and transpose of matrix A ;
$\text{trace}[A], \lambda_i[A], \ A\ _F$	trace, i th eigenvalue, and Frobenius norm of matrix A ;
$\oplus, \otimes$	matrix Kronecker sum and product operators.

For q -systems, indeterminate z is used; for δ -systems, we use c . In the 1-D case, corresponding q - and δ -systems are related by $q = 1 + \Delta\delta \Leftrightarrow z = 1 + \Delta c$, where Δ is a positive real constant, usually the sampling time. In the 2-D case, subscripts h and v denote the horizontally propagating (h.p.) subsystem (of size n_h) and vertically propagating (v.p.) subsystem (of size n_v) of the corresponding Roesser local s.s. model, $n = n_h + n_v$, $\Delta_{h,c}$ and $\Delta_{v,c}$ are positive real constants denoting "sampling times" along the h.p. and v.p. directions; three useful invertible matrices are $\Xi = \Delta_h I_{n_h} \oplus \Delta_v I_{n_v} \in \mathbb{R}^{n \times n}$, $\Xi_c = \Delta_h I_{n_h,c} \oplus \Delta_v I_{n_v,c} \in \mathbb{R}^{n \times n}$, and $\zeta = \Delta_v I_{n_h} \oplus \Delta_h I_{n_v} \in \mathbb{R}^{n \times n}$. I_{n_h} and I_{n_v} denote the $n_h \times n_h$ and $n_v \times n_v$ matrices $\Delta_h I_{n_h} \oplus \Delta_v I_{n_v}$ and $c_h I_{n_h} \oplus c_v I_{n_v}$. Corresponding 2-D q - and δ -systems are related by $q_h = 1 + \Delta_h \delta_h \Leftrightarrow z_h = 1 + \Delta_h c_h$ and $q_v = 1 + \Delta_v \delta_v \Leftrightarrow z_v = 1 + \Delta_v c_v$.

Subscripts h and v are used to differentiate between corresponding δ - and q -systems; for example, s.s. realization of a given DT system is either $\{A_h, B_h, C_h, D_h\}$ if implemented based on δ -operator or $\{A_q, B_q, C_q, D_q\}$ if implemented based on q -operator. The following notation is also used:

$$H(z_h, z_v) \big|_{z=c} = H(z_h, c_v) \big|_{c_v = (z_h - 1)/\Delta_h} \\ G(z_h, z_v) \big|_{z=c} = G(z_h, z_v) \big|_{\substack{z_h = 1 + \Delta_h c_h \\ z_v = 1 + \Delta_v c_v}}$$

Stability studies of 2-D q - and δ -systems involve the following regions:

$$\begin{aligned} \mathcal{L}_h^q &= \{(z_h, z_v) \in \mathbb{C}^2 : |z_h| < 1, |z_v| < 1\} \\ \mathcal{L}_h^\delta &= \{(z_h, c_v) \in \mathbb{C}^2 : |z_h + 1/\Delta_h| < 1/\Delta_h, \\ &\quad |c_v + 1/\Delta_v| < 1\} \\ \mathcal{T}_q^s &= \{(z_h, z_v) \in \mathbb{C}^2 : |z_h| = 1, |z_v| = 1\} \\ \mathcal{T}_c^s &= \{(z_h, c_v) \in \mathbb{C}^2 : |z_h + 1/\Delta_h| = 1/\Delta_h, \\ &\quad |c_v + 1/\Delta_v| = 1\}. \end{aligned}$$

A 2-D q -polynomial (δ -polynomial) that can vanish only in $\mathcal{L}_h^q$ ($\mathcal{L}_h^\delta$) is said to be *stable*.

Consider a linear, shift-invariant, strictly causal, p -input/ q -output 2-D system modeled via its $n_h, h=n_v, v$ Roesser local s.s. model $\{A_{hp}, B_{hp}, C_{vp}, D_{vp}\}$, viz. [3]

$$\begin{aligned} \begin{bmatrix} q_h[x^h](i,j) \\ q_v[x^v](i,j) \end{bmatrix} &= \begin{bmatrix} A_{hp}^{(1)} & A_{hp}^{(2)} \\ A_{vp}^{(1)} & A_{vp}^{(2)} \end{bmatrix} \begin{bmatrix} x^h(i,j) \\ x^v(i,j) \end{bmatrix} + \begin{bmatrix} B_{hp}^{(1)} \\ B_{vp}^{(1)} \end{bmatrix} \\ &\quad \cdot u(i,j) + [A_{vd}] \begin{bmatrix} x^h(i,j) \\ x^v(i,j) \end{bmatrix} + [D_{vd}] u(i,j) \\ y(i,j) &= [C_{vp}^{(1)} \quad C_{vp}^{(2)}] \begin{bmatrix} x^h(i,j) \\ x^v(i,j) \end{bmatrix} + [D_{vd}] u(i,j) \\ &\quad + [C_{vd}] \begin{bmatrix} x^h(i,j) \\ x^v(i,j) \end{bmatrix} + [D_{vd}] u(i,j) \end{aligned} \quad (2.1)$$

where $u \in \mathbb{R}^p, x^h \in \mathbb{R}^{n_h}, x^v \in \mathbb{R}^{n_v}$, and $y \in \mathbb{R}^q$. In addition, $A_{hp}^{(1)} \in \mathbb{R}^{n_h \times n_h}, A_{hp}^{(2)} \in \mathbb{R}^{n_h \times n_v}$, etc., and $(i,j) \in \mathbb{N}^2$. The operators $q_h[\cdot]$ and $q_v[\cdot]$ denote

$$q_h[x^h](i,j) = x^h(i+1,j) \quad \text{and} \quad q_v[x^v](i,j) = x^v(i,j+1). \quad (2.2)$$

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