A 3-D Integrator-Differentiator Double-Loop (IDD) Filter for Raster-Scan Video Processing

R. K. Bertschmann, N. R. Bartley and L. T. Bruton

***Abstract*— A novel RC-active circuit is proposed for the selective filtering of moving objects in raster-scanned analog video signals on the basis of their velocities. It consists of a feedforward continuous-time integrator and a two feedback loops with discrete-time differentiators in each loop. It has a frequency-planar passband in the 3-D space-time frequency domain.**

I. Introduction

TWO-DIMENSIONAL (2-D) RC-active recursive filters having direct-form structures have been proposed [1]-[3] for the direct processing of raster-scanned video signals. It has been shown that such filters are naturally suited to the processing of raster-scanned signals in real time and that the hardware implementation is generally much easier than in pure-digital filter implementations.

In this contribution, we describe a *three-dimensional* (3-D) RC-active recursive filter circuit for the processing of raster-scanned video signals. This circuit is derived from a ladder-form implementation of a first-order 3-D recursive Linear-Trajectory (LT) filter [4]-[8]. The circuit, which is less complex than the direct-form realization [1]-[3], consists of a continuous-time feedforward integrator (I) and two discrete-time feedback differentiators (D) in a double-loop (D) and is referred to here as the 3-D *I*ntegrator-*D*ifferentiator *D*ouble-Loop (*IDD*) circuit.

The signal-flow graph (SFG) of the proposed 3-D IDD filter circuit is derived from a passive 3-D continuous-domain prototype LR filter [4]-[8]. We briefly review the required passive LR filter prototype network in Section II. In Section III, we review raster-scanned signals and how they may be represented as 3-D mixed-domain signals. A suitable mixed-domain SFG is described in Section IV, which is obtained from the LR prototype filter network by means of elemental predistortion techniques [5],[6], followed by bilinear transformation. The RC-active 3-D IDD circuit is described in Section V along with experimental verification of the 3-D frequency response. The space-time performance of the circuit is briefly summarized in Section VI.

II. Review of 3-D LT Filters

MD continuous-domain prototype filters, comprised of inductive, capacitive and resistive elements, have been used as the basis for realizable filter structures [4]-[8]. The 3-D continuous-domain LT LR filter network shown in Fig. 1 possesses frequency-domain characteristics which make it useful for enhancing 3-D LT signals. The 3-D magnitude

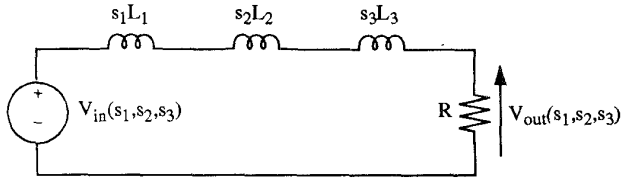

Fig. 1. A 3-D LT LR network

frequency response $M(\omega_1,\omega_2,\omega_3) = T(j\omega_1, j\omega_2, j\omega_3)$ is given by

$$M(\omega_1,\omega_2,\omega_3) = \frac{R}{\sqrt{R^2 + (\omega_1 L_1 + \omega_2 L_2 + \omega_3 L_3)^2}}. \quad (1)$$

$M(\omega_1,\omega_2,\omega_3)$ has a resonant plane given by

$$\omega_1 L_1 + \omega_2 L_2 + \omega_3 L_3 = 0 \quad \textbf{Resonant Plane} \quad (2)$$

and has -3dB planes given by

$$\omega_1 L_1 + \omega_2 L_2 + \omega_3 L_3 = \pm R. \quad \textbf{-3dB Planes} \quad (3)$$

The resonant plane passes through the origin and has unit normals $\mathbf{n}$ given by

$$\mathbf{n} = \frac{\pm 1}{||L||_2}(e_1 L_1 + e_2 L_2 + e_3 L_3), \quad L_1, L_2, L_3 \geq 0 \quad (4)$$

where $||L||_2 = \sqrt{L_1^2 + L_2^2 + L_3^2}$ and e_1, e_2, and e_3 are the orthogonal unit basis vectors in the $\omega_1, \omega_2, \omega_3$ directions. The perpendicular distance between the resonant and -3dB planes is $R/||L||_2$ and the 3-D Q-factor is defined in [4] as $Q = ||\omega||_2||L||_2/R$, where $||\omega||_2 = \sqrt{\omega_1^2 + \omega_2^2 + \omega_3^2}$.

III. Raster-Scanned Video Signals

Raster-scanning refers to the scanning of static 2-D images along closely spaced horizontal lines. This process is currently employed in commercial television systems such as that defined by the National Television Standards Committee (NTSC) [9]. In the NTSC standard, each static 2-D image, or *frame*, consists of 525 horizontal lines divided into two interlaced *fields*, one even and one odd, as shown in Fig. 2. The raster-scanning process in each frame

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scans the 262.5 odd-numbered lines, corresponding to the odd field, followed by the 262.5 even-numbered lines, corresponding to the even field. Frames are scanned in this way at the rate of 30 frames per second. The filter described in Sections IV and V processes each frame in exactly this sequence, or equivalently, *as the vertical concatenation of the odd and even fields.*

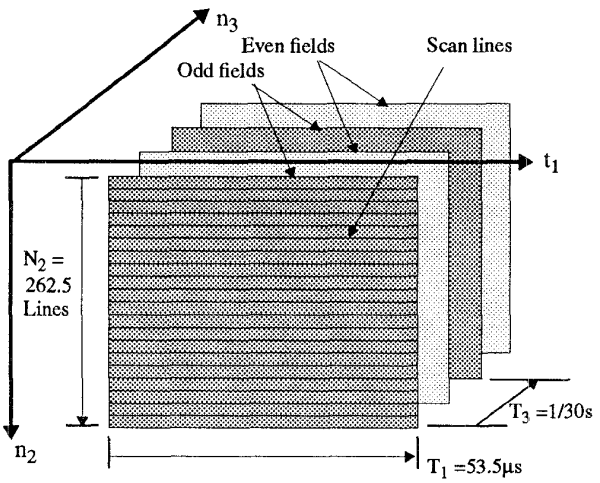

Fig. 2. An interlaced NTSC image sequence

Two consecutive lines of the raster-scanned video signal, as typically obtained from a scanning device such as a television camera, are shown in Fig. 3. This signal is *continuous-domain* in the row dimension t_1; that is, $t_1 \in [0; T_1]$, $t_1, T_1 \in \Re^1$, where $T_1 = 53.5\mu s$. At the end of the line, a horizontal synchronization pulse indicates that scanning is to begin on the next horizontal line. Thus, the raster-scanned video signal is *discrete-domain* in the column variable n_2; i.e., $n_2 \in [0; N_2)$, $n_2, N_2 \in \mathbf{N}^1$, where $N_2 = 525$ lines. Similarly, vertical synchronization pulses are inserted at the completion of each field and frames are counted after the completion of every even field. Thus, the raster-scanned video signal is also *discrete-domain* in the temporal variable n_3; i.e., $n_3 \in [0; \infty] \in \mathbf{N}^1$. The corresponding scanned 3-D image may therefore be represented as a 3-D mixed-domain signal $x(t_1, n_2T_2, n_3T_3)$ having domain $dmn[x(t_1, n_2T_2, n_3T_3)] \in \Re^1 \times \mathbf{N}^2$, where $T_2, T_3 \in \Re^1$ are the column and temporal sample intervals, respectively.

IV. Mixed-Domain Ladder-Form SFG of the 3-D LT Filter

In the field of 1-D signal processing, SFG simulation of LCR ladder filters has received a great deal of attention [10]-[12]. The extension of this work to the field of M-D signal processing has recently been explored [5],[6]. In [5],[6], the authors investigate the design of 3-D discrete-domain ladder-form structures from prototype 3-D LCR networks corresponding to LT filters and Plane-Wave (PW) filters. They propose a technique of elemental predistortion for obtaining *realizable* 3-D discrete-domain SFGs using the bilinear transformation. We propose to modify this technique

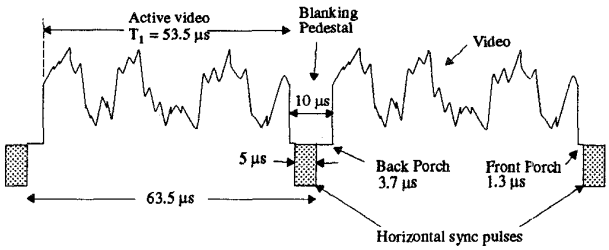

Fig. 3. Two lines from a raster-scanned video signal

here to obtain a realizable 3-D mixed-domain ladder-form SFG suitable for processing raster-scanned signals.

The proposed predistorted LR prototype network, corresponding to Fig. 1, is shown in Fig. 4. As shown, negative resistances $-r_2$ and $-r_3$ have been placed in series with the immittances s_2L_2 and s_3L_3, respectively. The input-output Laplace transform voltage transfer function $T(s_1, s_2, s_3)$ is clearly unaltered by these predistortions by the introduction of positive compensating resistances r_2 and r_3 in series with the terminating resistance R, as shown in Fig. 4.

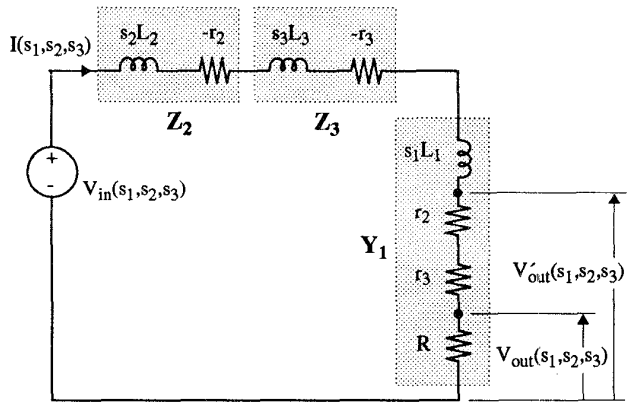

Fig. 4. The predistorted 3-D LR network

A simple Type I SFG [5][12] corresponding to the predistorted network in Fig. 4 is obtained, after some manipulation, and is shown in Fig. 5. This SFG contains a lossy integrating branch $\mathbf{Y_1}$ having branch transmittance $b_1(s_1)$, as indicated, and two lossy differentiating branches $\mathbf{Z_2}$, $\mathbf{Z_3}$ having branch transmittances $b_2(s_2)$ and $b_3(s_3)$, also as indicated. Note that the output node in Fig. 5 is $V'_{out}(s_1, s_2, s_3)$, which is the voltage shown in Fig. 4. This differs from the desired $V_{out}(s_1, s_2, s_3)$ only by a constant scaling factor α, where $V'_{out}(s_1, s_2, s_3) = \alpha V_{out}(s_1, s_2, s_3)$ and $\alpha = (R + r_2 + r_3)/R$.

The mixed-domain SFG is obtained from the predistorted continuous-domain SFG in Fig. 5 by applying the bilinear transformation to the transmittances $b_2(s_2)$ and

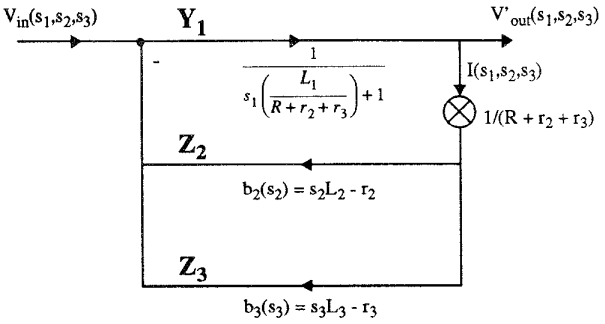

Fig. 5. Type I SFG of the predistorted LR network

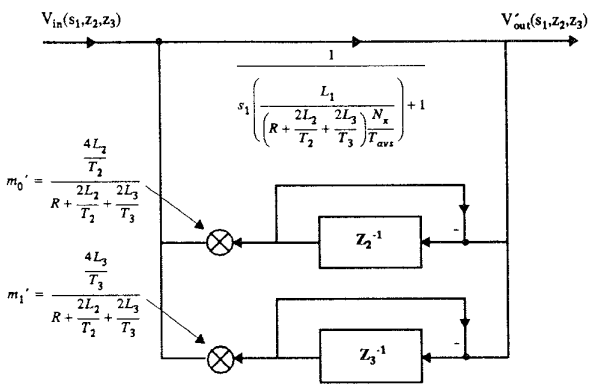

Fig. 6. The mixed-domain SFG of the 3-D IDD filter

$b_3(s_3)$ according to

$$b_i(z_i) = b_i(s_i)|_{\frac{2}{T_i}\frac{z_i-1}{z_i+1}} = \frac{2L_i}{T_i}\frac{z_i-1}{z_i+1} - r_i, \quad i = 2,3 \tag{5}$$

We choose

$$-r_i = -\frac{2L_i}{T_i} \qquad i = 2,3 \tag{6}$$

so that equation (5) simplifies to

$$b_i(z_i) = -\frac{4L_i}{T_i}\frac{1}{z_i+1}, \quad i = 2,3 \tag{7}$$

Each of $b_i(z_i)$, i=2,3 in equation (7) is easily implemented in the resulting mixed-domain SFG *without a delay-free forward path* [5].

Following the bilinear transformation of $b_2(s_2)$ and $b_3(s_3)$ in this way, it is necessary to scale s_1 in branch $b_1(s_1)$ in an equivalent way in order to restore the correct passband orientation in the resulting mixed-domain filter. For this, it is appropriate to use ks_1 where

$$k = \frac{T_{avs}}{N_1} \tag{8}$$

where $T_{avs} = \frac{3}{4}T_1 = 40.125\mu s$ is the aspect ratio-corrected portion of each scan line and $N_1 = 243$ is the number of visible lines in each field. This performs the equivalent scaling operation to sampling N_1 pixels in each continuous-domain raster-scan line in T_{avs} seconds.

The final mixed-domain SFG is shown in Fig. 6 and has an input-output voltage transfer function given by

$$T(s_1, z_2, z_3) = \frac{R + r_2 + r_3}{R + \frac{T_{avs}}{N_1}s_1L_1 + \sum_{i=2}^{3}\frac{2}{T_i}\frac{z_i-1}{z_i+1}L_i} \tag{9}$$

and a frequency response given by

$$T(j\omega_1, j\Omega_2, j\Omega_3) = \frac{R + r_2 + r_3}{R + j\frac{T_{avs}}{N_1}\omega_1L_1 + \sum_{i=2}^{3} j\frac{2}{T_i}\tan(\frac{\Omega_i}{2})L_i} \tag{10}$$

V. The 3-D IDD RC-Active Circuit Realization

The mixed-domain 3-D IDD SFG in Fig. 6 has been implemented using the simple RC-active 3-D IDD circuit shown in Fig. 7. The circuit employs wide-bandwidth operational amplifiers (GBW = 100MHz) along with a digitally sampled row delay and frame delay. The row and frame delays, for the discrete-time differentiators, have been constructed using 8-bit video A/D and D/A converters and they each buffer digitized video data through high-speed static RAM. The row delay z_2^{-1} samples at a rate of 12.1 MHz (or 768 samples per line) and achieves a row delay of precisely 63.5 μs. The frame delay z_3^{-1} samples at a rate of 7.86 MHz (or 262144 samples per frame) and achieves a frame delay of precisely 1/30 s.

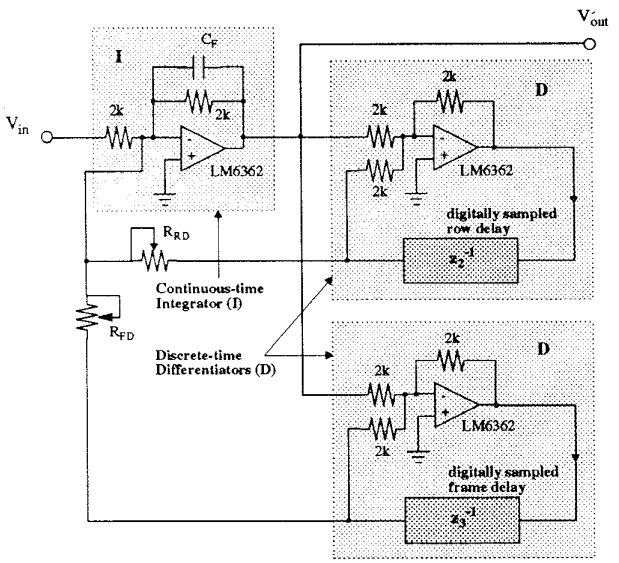

Fig. 7. The proposed RC-active 3-D IDD circuit

We have designed and implemented a 3-D IDD mixed-domain LT filter with $L_1 = 12$, $L_2 = 2.5$, $L_3 = 9$, and $R = 1$, corresponding to a 3-D Q-factor [4] of $Q = 15.21||\omega||_2$, and using the normalized bilinear transformation with $T_2 = T_3 = 1$. The component values in the circuit of Fig. 7 are $R_{FD} = 1333\Omega$, $R_{RD} = 4800\Omega$, and $C_F = 41.28pF$.

To experimentally verify the 3-D frequency response of

the 3-D LT IDD circuit, dynamic analog gray-scale 3-D sinusoidal images have been generated and displayed on a CRT screen. A television camera has been focused on the CRT display and used to obtain the composite video raster-scan input signal V_{in} to the 3-D IDD circuit. The amplitudes of the sinusoidal input and output raster-scan signals have been carefully measured to determine the gain frequency response $M(k\omega_1, \Omega_2, \Omega_3)$ of the filter.

The resonant plane for this filter, from (10), is given by

$$\frac{T_{avs}}{N_1}\omega_1 L_1 + 2\tan(\frac{\Omega_2}{2})L_2 + 2\tan(\frac{\Omega_3}{2})L_3 = 0 \qquad (11)$$

This plane is shown as a surface plot in Fig. 8. Also shown in Fig. 8 are lines $\mathbf{L_1}$ and $\mathbf{L_2}$ that are parallel to the Ω_3 axis and intersect the resonant plane at points $\mathbf{P_1}$ and $\mathbf{P_2}$, respectively. Gain frequency response measurements have been taken along one such line, $\mathbf{L_1}$, and are shown with the calculated response in Fig. 9. As shown, the measured peak accurately aligns with the point $\mathbf{P_1}$ and the roll-off confirms the selectivity of the filter, within measurement error. Although not shown here, similar results have been obtained along line $\mathbf{L_2}$.

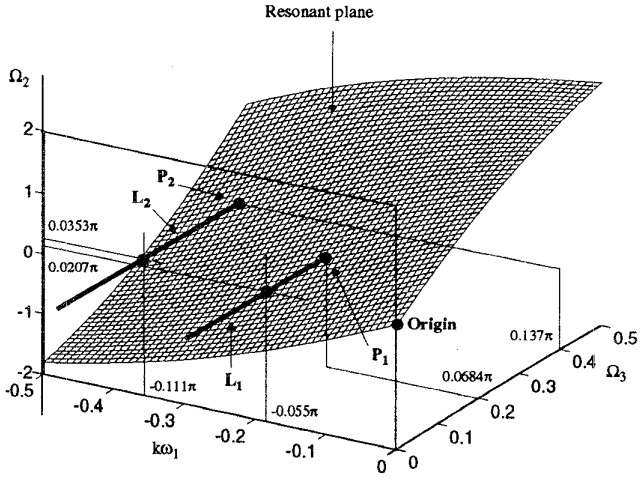

Fig. 8. Frequency response of mixed-domain 3-D LT filter

VI. Experimental Space-Time Performance

Experimental verification of the space-time response of the circuit has been obtained, but is omitted for brevity. A moving passband object, having a space-time linear trajectory of (1.33, 0.28) pixels per frame, has been processed using Fig. 7 and the displayed NTSC raster-scan output V'_{out} is a good video replica of the input. When the trajectory of the object is altered to a stopband value, for example to (-1.33, 0.28) pixels per frame, the output object is significantly attenuated.

VII. Conclusion

An analog RC-active circuit is proposed using a continuous-time feedforward integrator and two discrete-time feedback differentiators. This 3-D IDD circuit selectively enhances moving objects in raster-scanned video signals if the objects have specific velocities that correspond to the orientation of the frequency-planar passband. Objects having other velocities are in the stopband and are appropriately attenuated. To our knowledge, this is the first real-time 3-D recursive filter that has been reported in the literature.

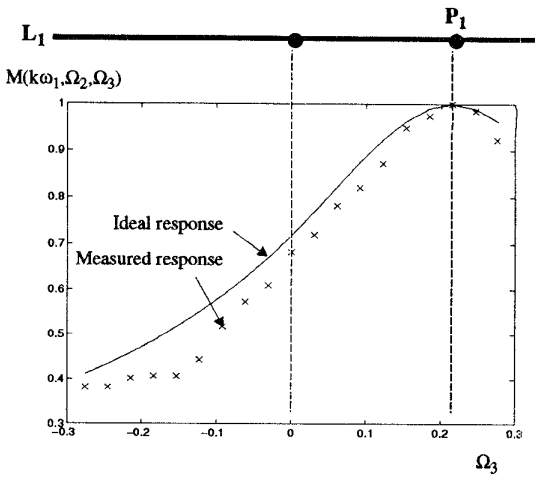

Fig. 9. Measured and actual frequency response along $\mathbf{L_1}$

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