Transients in Reconfigurable Signal Processing Channels

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***Abstract*—System reconfiguration at run time may cause unacceptable transients. In this paper, a new design methodology is proposed for reducing transients due to reconfiguration in recursive digital signal processing (DSP) systems. The technique utilizes the fact that, 1) transfer functions can be realized by different processing structures, and 2) these alternative realizations show different transient properties when reconfigured in one step. By selecting processing structures that are less prone to reconfiguration transients, i.e., generate smaller transients due to the abrupt change of coefficients, transients can be reduced for a wide-range of input–output mappings. Selection of the preferable structures is based on the evaluation and control of the dynamic range of the internal variables.**

***Index Terms*—Infinite impulse response filters, reconfigurable system, reconfiguration, reconfiguration method, reconfiguration transient, signal processing, state variables, structure dependence, transient reduction, transients.**

I. Introduction

RECONFIGURABLE digital signal processing (DSP) systems play an important role in the design and implementation of larger scale, model-based, distributed monitoring and control applications [1]–[3] because monitoring and control in a changing environment may require the reconfiguration of the incorporated model of the environment and/or other system components. The concept of system with modes of operation (SMO) has been proposed in the literature [2] as a possible framework for reconfigurable model-based system implementations. In an SMO, the model changes are represented as transitions between modes. Modes and possible transitions are set up during the design phase or inserted at run-time. Some modes are classified as operational modes, and other modes are failure modes corresponding to failure conditions in the system or in the environment. Generally, mode transitions are considered as being bi-directional, i.e., mode transition can occur in both directions. For every mode, there exists at least one configuration, which defines all the necessary realization details.

In our paper, we investigate some aspects of these problems for infinite impulse response (IIR) signal processing channels, i.e., when the system realizes IIR filters in its modes, excited by white noise inputs. In our experimental setup, the signal processing channels are to be reconfigured abruptly, in one step, to represent mode transitions in the built-in model. The one-step reconfiguration of the coefficients, in short, the one-step reconfiguration method, removes the old system and inserts the new system into operation in one step between two consecutive iterations. Parallel with the configuration change, it copies the state-variables of the old system unmodified into the new system. Efficient implementations of the one-step reconfiguration method exist for digital signal processors, general purpose CPUs, and field programmable gate arrays. The one-step reconfiguration method utilizes the fact that the state variables store valuable information about the previous input samples, so we can, hopefully, continue operation of the new system producing smaller transients than transients produced by systems reconfigured by other ways.

Unfortunately, the one-step reconfiguration is marked as poorly performing in reconfigurable IIR filters based on simulations [1]. Here we show that these unfavorable transient properties are due to the applied filter structure, and by selecting other structures the transient properties of the one-step reconfiguration can be improved dramatically. Fortunately, the preferable structures provide not only improved transient properties, but these are suitable for fast hardware or software implementations, and these are not sensitive to the effects of fixed-point implementations.

After a short introduction to the reconfiguration transients in Section II, we present some possible reconfiguration strategies in Section III. In Section IV, we investigate the one-step reconfiguration method for the case of IIR filters. An estimate of reconfiguration transients is given in Section V for white noise inputs, that lets us select preferable filter structures. We present a practical example in Section VI, which shows that the reconfiguration transients depend on the actual DSP structure, and that the transients can be reduced by orders of magnitude by selecting a suitable filter structure. Finally, conclusions are drawn in Section VII.

II. Reconfiguration Transients

The run-time reconfiguration brings up several open questions both in the field of DSP realization and DSP system design. This paper concentrates on the issue of the intermediate disturbances, in other words, reconfiguration transients, caused by the abrupt change in the DSP system. These reconfiguration transients originate from the differences of the behavior of the system before and after the reconfiguration. Reconfiguration transients might not be tolerated because of their possibly high amplitude and extreme dynamics [4], [5]. For example, these

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transients manifest themselves in control systems as wide deviations from the expected controlled variables, saturations, and even system component failures due to overload [1]. In audio signal processing, the transients are heard as disturbing clicks and pops in the audio signal [5], while they appear as disturbing image artifacts in video processing [6].

The optimal transition of a reconfigured system is highly environment- and system-dependent; therefore, various transient definitions and transient measures exist. The appropriate one can be selected based on the requirements and transient tolerance of the environment in which the system operates. The transient is defined generally as

$$f_{tr}(n) = f(n) - f_{id}(n) \tag{1}$$

where

- $f_{tr}(n)$ transient of the variable;
- $f(n)$ observed variable in the investigated reconfigurable system;
- $f_{id}(n)$ same variable observed in an ideal reconfigurable system.

In addition to the definition of the transient, a transient measure is required to compare transients of contending alternatives for transient reduction. The average energy of the transient, defined as

$$\|\mathbf{f}_{tr}\|_2^2 = \sum_{n=-\infty}^{\infty} |f_{tr}(n)|^2 \tag{2}$$

is the appropriate selection of measure for white noise inputs.

III. Reconfiguration Methods

A mode transition means that the underlying realization is to be reconfigured. This reconfiguration is done by a reconfiguration method. Generally, the task of the reconfiguration method is to transform the system to the new configuration corresponding to the just reached mode as soon as possible and with minimal transient. There are various reconfiguration methods proposed in the literature to realize the run-time configuration changes due to mode transitions, see [1], and [7] for overviews, and [5] for methods used in speech processing and synthesis. The common approaches are the following:

1) one-step reconfiguration;
2) multiple step reconfiguration with the gradual variation of the intermediate configurations using interpolation (series of one-step reconfigurations);
3) input cross-fading methods;
4) output cross-fading methods;
5) state variable update methods;
6) signal smoothing.

The most cited reconfiguration method is the output switching method, a simple form of the output cross-fading method, which assumes parallel implementation of all the configurations used during the lifetime of the system and selects the appropriate one as system output via an output switch. The output switching method has favorable transient properties but it has mostly theoretical importance because it is not feasible to allocate resources for a large number of configurations in parallel [7], even if certain compromises are made [5].

On the other hand, the one-step reconfiguration is found to be easy to implement, and it requires minimal computing overhead on the speed critical execution path of DSP systems, but there is an open debate on the transient properties of this reconfiguration method [1], [5], [8]. Although the relative simplicity of implementation allows us to use this method in series to reduce transients even further (by interpolating and installing intermediate configurations without excessive computational overhead [9]), the understanding of the transient properties of this method is essential.

IV. Reconfiguration of IIR Filters

Signal processing channels are linear IIR systems, in essence, linear dynamic input–output mappings defined by the impulse response in the time-domain or by the transfer function in the frequency-domain. Both descriptions are input–output descriptions; they do not specify how the internal processing is done in the filter. From now, we consider the realization of a transfer function; therefore, the task can be given to realize an IIR filter with a time-varying conceptual transfer function in the form of $H(n, z)$ with low transient. The transfer function is only defined for $\mathbf{x}(0) = 0$, where $\mathbf{x}$ is the state variable vector, so the transfer function cannot be used as a system description. The linear time-invariant state variable description (SVD), in the form of

$$\begin{aligned}\mathbf{x}(n+1) &= \mathbf{A}\mathbf{x}(n) + \mathbf{B}\mathbf{u}(n)\\ \mathbf{y}(n) &= \mathbf{C}\mathbf{x}(n) + \mathbf{D}\mathbf{u}(n)\end{aligned} \tag{3}$$

is sufficient to investigate the transients of the one-step reconfiguration method between consecutive reconfigurations. From now, we will consider only SVDs which are minimal in the sense of state variables and have a nonsingular $\mathbf{A}$ with full eigenvector system. The transfer function $H(z)$ is invariant to the transformations

$$(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}) \leftarrow \left(\mathbf{T}^{-1}\mathbf{A}\mathbf{T}, \mathbf{T}^{-1}\mathbf{B}, \mathbf{C}\mathbf{T}, \mathbf{D}\right) \tag{4}$$

where $\mathbf{T}$ is a nonsingular transformation matrix. Equation (4) means that there exist an infinite number of SVDs that realize the same transfer function. Various IIR filter structures [10], [11] have been developed to utilize this invariance of the realized transfer function to the SVD to achieve certain advantages, in most cases better performance under finite word-length realizations.

In our investigation, we consider the transients of one reconfiguration only at $n = k$. We compare the transients produced by our systems to the output switching method. The experimental setup is shown in Fig. 1. We assume, that the examined components, $H(n, z)$, $H_{old}(z)$, and $H_{new}(z)$, are in steady-state, or at least very close to that, before the reconfiguration. After the reconfiguration, the state variables inherited from the old configuration [$H(n, z)$ with $\mathbf{A}_{old}$, $\mathbf{B}_{old}$, $\mathbf{C}_{old}$, and $\mathbf{D}_{old}$] are not steady states for the new configuration [$H(n, z)$ with $\mathbf{A}_{new}$, $\mathbf{B}_{new}$, $\mathbf{C}_{new}$, and $\mathbf{D}_{new}$] in all practical cases. The transient of

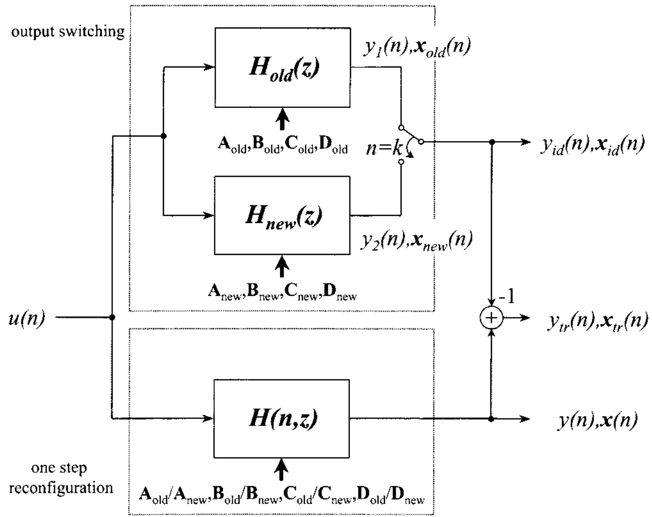

Fig. 1. Experimental setup to compare the transient properties of the output switching and the one-step reconfiguration.

the state variable vector $\mathbf{x}_{tr}(k)$ is the difference of the state variable vector of $H_{new}(z)$ and the state variable vector of $H(n, z)$, which is identical to the state variable vector of $H_{old}(z)$. Therefore, the transient of the state variable vector in the system reconfigured by the one-step reconfiguration can be expressed as

$$\mathbf{x}_{tr}(k) = \mathbf{x}_{old}(k) - \mathbf{x}_{new}(k) \tag{5}$$

and the output transient can be computed as

$$\mathbf{y}_{tr}(n) = \begin{cases} 0, & \text{for } 0 \le n < k \\ \mathbf{C}_{new}\mathbf{A}_{new}^{n-k}\mathbf{x}_{tr}(k), & \text{for } n \ge k. \end{cases} \tag{6}$$

More general characterizations of the transient problem can be given for certain classes of inputs such as sinusoid, finite energy, or white noise inputs. This characterization leads to constructive rules to select filter structures with low reconfiguration transients for the given class of input sequences. Here, we will consider only white noise inputs, but the discussion can be extended for other classes of inputs based on how they effect the internal energy relationships in the filter. A similar investigation was presented in [7] for sinusoid inputs leading to different structural requirements than here.

V. White Noise Inputs

Based on (5) and (6), it is possible to estimate the energy of the internal state variables, and the output transient for white noise inputs. Here, we present an estimate of the output transient energy, which gives us a direct way to select filter structures with low transients. (5) shows that the state variables play a central role in defining reconfiguration transients in IIR filters. By expressing the covariance matrix $\mathbf{K}$ of the state variables, in other words the controllability Grammian, defined as

$$\mathbf{K} = E\left[\mathbf{x}(n)\mathbf{x}^T(n)\right] \tag{7}$$

one can estimate the energy relationships of the state variables of a filter. The matrix $\mathbf{K}$ can be computed from the SVD as

$$\mathbf{K} = \sum_{l=0}^{\infty} \left(\mathbf{A}^l\mathbf{B}\right)\left(\mathbf{A}^l\mathbf{B}\right)^T = \mathbf{AKA}^T + \mathbf{BB}^T. \tag{8}$$

Equation (6) defines how the transient error at the reconfiguration settles. The process of the settling in terms of energies is controlled by the observability Grammian $\mathbf{W}$, the dual of $\mathbf{K}$. Matrix $\mathbf{W}$ is computed as

$$\mathbf{W} = \sum_{l=0}^{\infty} \left(\mathbf{CA}^l\right)^T \left(\mathbf{CA}^l\right) = \mathbf{A}^T\mathbf{WA} + \mathbf{C}^T\mathbf{C}. \tag{9}$$

The matrices $\mathbf{K}$ and $\mathbf{W}$ play essential roles in the theory of investigation of finite wordlength effects in IIR filters as shown in [10].

For reconfiguration transients we need to estimate the average output transient in the form of

$$E\left[\sum_{l=0}^{\infty} y_{tr}^2(l)\right]. \tag{10}$$

With direct substitutions of (5) and (6) into (10), and using the definition (9)

$$\begin{aligned} E\left[\sum_{l=0}^{\infty} y_{tr}^2(l)\right] &= E\left[\sum_{l=k}^{\infty}\left(\left(\mathbf{C}_{new}\mathbf{A}_{new}^{l-k}\mathbf{x}_{tr}(k)\right)^T \right.\right. \\ &\qquad \left.\left.\left(\mathbf{C}_{new}\mathbf{A}_{new}^{l-k}\mathbf{x}_{tr}(k)\right)\right)\right] \\ &= E\left[\mathbf{x}_{tr}^T(k)\mathbf{W}_{new}\mathbf{x}_{tr}(k)\right] \\ &= E\left[\sum_{j=1}^{N}\sum_{i=1}^{N} w_{new,\,ij}x_{tr,\,i}(k)x_{tr,\,j}(k)\right] \\ &= \sum_{j=1}^{N}\sum_{i=1}^{N} w_{new,\,ij}E[x_{tr,\,i}(k)x_{tr,\,j}(k)]. \end{aligned} \tag{11}$$

From (11)

$$E\left[\sum_{l=0}^{\infty} y_{tr}^2(l)\right] = \sum_{j=1}^{N}\sum_{i=1}^{N} w_{new,\,ij}E[x_{tr,\,i}(k)x_{tr,\,j}(k)] \tag{12}$$

can be derived because $\mathbf{x}_{tr}^T(k)\mathbf{W}_{new}\mathbf{x}_{tr}(k)$ is a quadratic form and $\mathbf{W}$ is a real symmetric matrix. The scalar N stands for the order of the filters.

Let us define the covariance matrix of the state variables transient at $n = k$ as

$$\mathbf{K_{tr}} = E\left[\mathbf{x}_{tr}(k)\mathbf{x}_{tr}^T(k)\right] \tag{13}$$

which can be converted by substitutions to

$$\begin{aligned} \mathbf{K_{tr}} &= E\left[\mathbf{x}_{tr}(k)\mathbf{x}_{tr}^T(k)\right] = \mathbf{K}_{old} + \mathbf{K}_{new} \\ &\quad - E\left[\mathbf{x}_{old}(k)\mathbf{x}_{new}^T(k)\right] - E\left[\mathbf{x}_{new}(k)\mathbf{x}_{old}^T(k)\right]. \end{aligned} \tag{14}$$

The first two terms are the observability Grammians of the old ($\mathbf{K}_{old}$) and the new filter ($\mathbf{K}_{new}$). The last two cross terms are the covariance of the state variables of the new and the old filter

TABLE I
AVERAGE ENERGY OF OUTPUT TRANSIENT BASED ON OUR ESTIMATION [$Tr(\mathbf{W}_{new}\mathbf{K}_{tr})$] FOR DIFFERENT FILTER STRUCTURES

Structure	Decreasing bandwidth	Increasing bandwidth
Direct structure II transposed	$8.5653\,10^8$	2.6681
Parallel	2.5123	$2.0047\,10^8$
Resonator-based (orthogonal)	4.3685	4.5985
Normalized lattice (orthogonal)	4.8686	4.9399

TABLE II
AVERAGE ENERGY OF THE OUTPUT TRANSIENT FROM 10 000 EXPERIMENTS

Structure	Decreasing bandwidth	Increasing bandwidth
Direct structure II transposed	$8.7510\,10^8$	2.6987
Parallel	2.5268	$2.2190\,10^8$
Resonator based (orthogonal)	4.3485	4.5829
Normalized lattice (orthogonal)	4.8658	4.9413

showing how similar the two filters are. Here we use the stationary property of $\mathbf{x}_{tr}$ defined in (5). The elements of matrix $\mathbf{K_{tr}}$ are just exactly the $E[x_{tr,i}x_{tr,j}]$ terms in (12); therefore, a direct substitution is possible and (12) can be rewritten in a matrix form as

$$E\left[\sum_{l=0}^{\infty} y_{tr}^2(l)\right] = Tr(\mathbf{W}_{new}\mathbf{K}_{tr}). \tag{15}$$

Both the $\mathbf{W_{new}}$, and the $\mathbf{K_{tr}}$ matrices depend only on the used filter structure and the realized transfer functions.

VI. EXAMPLE

As an example, four filter structures realizing 10th order pass-band Butterworth filters with the center frequency $f_c = 0.1 f_s/2$, and bandwidth $B_{wide} = 0.1 f_s/2$ for the wide-band, and $B_{narrow} = 0.01 f_s/2$ for the narrow-band filter are designed. The filter structures are the transposed direct structure II, the parallel, the l_2 scaled orthogonal resonator-based structure [11], and the l_2 scaled orthogonal reverse normalized lattice structure [12].

Table I shows the theoretical estimates of the average output transient energy of the previously listed filters. Table II lists the average energy of the output transients observed in simulations using the experimental setup of Fig. 1. The simulation consisted of 10 000 experiments for an identical set of filters.

As the theory predicts, the direct structure and the unscaled parallel structure produce very high energy transients in one of the mode changes. Mode changes are considered bi-directional; therefore, the application of the direct and unscaled parallel structures are not suggested in reconfigurable systems using the one-step reconfiguration method. The l_2 scaled orthogonal resonator-based and the reverse normalized lattice structures produce the lowest transients overall, independent of the direction of the mode change. Orthogonality of these structures assures that $\mathbf{K} = \mathbf{I}$, independent of the realized transfer function limiting $\mathbf{K}_{tr}$, and $\mathbf{W}_{new}$ has very good properties too. The transient of the direct and parallel structures can be orders of magnitude bigger than the same filters realized by the l_2 scaled orthogonal structures.

VII. CONCLUSION

The work presented here shows that the energy represented by the state variables and the output play a central role in defining reconfiguration transients of IIR filters when the one-step reconfiguration method is used. The elaborated estimation of the average output transients, which depends only on the filter structure and the realized transfer function for white noise inputs, is closely aligned with the simulation results. According to our investigation, by selecting suitable realization structures, namely orthogonal structures, the transient properties of the one-step reconfiguration can come close to those of the output switching. The transients are reduced to orders of magnitude smaller than transients observed in other structures such as the direct structure, while the advantageous implementation related properties of the one-step reconfiguration method are kept.

REFERENCES

[1] J. Sztipanovits, D. M. Wilkes, G. Karsai, C. Biegl, and L. E. Lynd, "The multigraph and structural adaptivity," *IEEE Trans. Signal Processing*, vol. 41, pp. 2695–2716, Aug. 1993.

[2] L. Barford, E. J. Manders, G. iswas, P. J. Mosterman, V. Ram, and J. Barnett, "Derivative estimation for diagnosis," in *Proc. 1999 IEEE Int. Workshop Emerging Technol.*, Venice, Italy, May 1999, pp. 9–15.

[3] M. S. Moore, "Model-integrated program synthesis for real-time image processing," Ph.D. dissertation, Vanderbilt Univ., Nashville, TN, May 1997.

[4] T. Kovácsházy and G. Péceli, "Transients in adaptive and reconfigurable measuring channels," in *Int. Symp. Meas. Technol. Intelligent Instrum.*, vol. 1, Miskolc, Hungary, Sept. 1998, pp. 247–252.

[5] V. Välimäki and T. I. Laakso, "Suppression of transients in variable recursive digital filters with a novel and efficient cancellation method," *IEEE Trans. Signal Processing*, vol. 46, pp. 3408–3414, Dec. 1998.

[6] J. M. Winograd, "Incremental refinement structures for approximate signal processing," Ph.D. dissertation, Boston Univ., Boston, MA, Feb. 1997.

[7] T. Kovácsházy and G. Péceli, "Scaling strategies for reconfigurable digital signal processing systems," *IEEE Int. Workshop Intelligent Signal Processing*, vol. 1, pp. 215–220, Aug. 1999.

[8] G. Péceli and T. Kovácsházy, "Transients in reconfigurable DSP systems," *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 986–989, Oct. 1999.

[9] T. Kovácsházy, "Reconfiguration methods for DSP systems," in *Proc. IMEKO'96 Int. Symp.*, Budapest, Hungary, 1996, pp. 180–183.

[10] R. A. Roberts and C. T. Mullis, *Digital Signal Processing*. New York: Addison-Wesley, 1987.

[11] M. Padmanabhan, K. Martin, and G. Péceli, *Feedback-Based Orthogonal Digital Filters*. Norwell, MA: Kluwer, 1996.

[12] J. Chung and K. K. Parhi, *Pipelined Lattice and Wave Digital Filters*. Norwell, MA: Kluwer, 1996.

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